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ACQUISITION AND REDUCTION BY ON-LINE COMPUTER
OF CAPILLARY PRESSURE DATA FROM PURCELL CELL

BY



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A THESIS

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The undersigned hereby certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Acquisition and Reduction by On-Line Computer of Capillary Pressure Data from Purcell Cell" submitted by Rashid Mahmud, B.Sc. Eng., in partial fulfillment of the requirements for the degree of Master of Science in Petroleum Engineering.

ABSTRACT

Equipment has been designed and constructed and a program has been developed for on-line data acquisition and reduction from mercury-capillary pressure apparatus by means of the IBM 1800 computer.

The usefulness of this approach is evident from the fact that the permeabilities obtained by the use of on-line equipment were observed to have a lower standard deviation than the permeabilities obtained by the use of manually-operated equipment. Approximately one hour was required to run one core and to obtain the capillary pressure curve and the permeability. This is about one-sixth the time normally required if manually-operated equipment is used.

The least squares fit for the capillary pressure data was not entirely satisfactory, but the capillary pressure curves show that most of the pore volume of the cores consists of large pores in which mercury can be injected at low pressures.

Since the core samples were taken from a continuous ten-foot section, therefore, it would be expected that the lithology factor of the cores does not vary much. From the results, this was observed to be correct.

It was also observed that by neglecting the effect of expansion of the mercury cell and contraction of the mercury with pressure, a maximum error of -1.05 percent was introduced in the permeability results. However, the neglect of the above effect introduces an error of 7 percent in the fraction of pore volume filled with mercury.

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INTRODUCTION

Because the measurement of capillary pressure is a tedious and time-consuming process, capillary effects are generally ignored when modelling the porous medium.

The mercury injection method of W. R. Purcell¹⁸ has proved especially suitable for measuring capillary pressure curves on core samples having low permeability. Compared to the restored state technique which requires the use of a semipermeable membrane, the procedure of Purcell offers the advantages of being less time-consuming and allowing measurement of a greater range of capillary pressures. The data obtained by the mercury injection technique can be put to many other uses besides obtaining the capillary pressure curve. For example, it can be used to (1) determine the permeability of the core by Purcell's or Burdine's⁵ method, (2) obtain the pore size distribution curves, (3) obtain the family of capillary pressure curves for different values of pore geometrical factors²⁵, (4) determine the surface area of the porous medium³, (5) predict the susceptibility of a sand to effective flood action¹⁰.

Keeping in view the uses to which mercury capillary pressure data can be put, the purpose of this work was to use Purcell's technique to obtain mercury capillary pressure curves, and to calculate permeability from the data obtained by hooking up the manually-operated Purcell's cell to the IBM 1800 computer. By doing this, the time required to obtain the mercury capillary pressure and the permeability was considerably reduced and the accuracy of the results was increased.

Pressure and linear displacement transducers were used to feed directly into the computer the values of the pressure and the

volume of mercury injected.

The various operations such as (1) reading of a specific transducer, (2) the manipulating of the data, (3) the plotting of some specific datum points, (4) the fitting of the best curve through a set of datum points, (5) the calculating of the area under the best fit curve, (6) the calculating of the permeability, (7) the printing of the results, were all controlled by the help of binary digital switches at the operator's end and by the mainline and subprograms.

It was observed that about forty-five minutes to one hour was required to run a core, to determine the capillary pressure curve, and to calculate the permeability. This time is about one-sixth the time normally required if manually-operated equipment is used. This partially automated mercury capillary pressure equipment can now be used for routine core analysis.

REVIEW OF LITERATURE

Early investigations of problems encountered in secondary recovery led to the discovery of many of the fundamental concepts of fluid flow in porous media. As research in secondary recovery progressed, it became increasingly apparent that many of the variables in laboratory tests could not be evaluated due to the lack of knowledge of certain fundamental physical properties of the fluids and porous media involved.

One such fundamental characteristic of porous media and reservoir fluids is the capillary pressure-saturation relation of a medium and the fluid with which it is saturated. Capillary pressure data has been used in a qualitative sense to explain certain reservoir properties. In a quantitative sense it can be applied to the determination of the connate water saturation of certain sands.

The application of capillary pressure data to secondary recovery problems includes the determination of connate water saturation, minimum residual oil saturations, wetting characteristics, and other fundamental properties.

In 1941 Leverett¹³ presented a paper which gave the essential concepts of capillary behavior in porous solids. His presentation included both theoretical and experimental aspects of the problem. He defined the term "capillary pressure" and applied it to an ideal porous system. His work included the definition of a dimensionless quantity which was a function of fluid saturation and which could be correlated with porosity and permeability for clean unconsolidated sands. His experimental work was performed by the drainage of water from packed columns of unconsolidated sands.

Subsequently, other authors have presented experimental techniques which permit the determination of capillary pressure data on small core samples. Data have been presented on porous systems other than unconsolidated sand and with the use of liquids other than water. Notable among these are the works of Hassler, Brunner, and Deahl ⁹, Bruce and Welge ⁴, Amyx and Yuster ², and Purcell ¹⁸. Others have indicated the applicability of such data to field problems without regard to the theoretical aspects of the capillary pressure saturation function.

It is not possible to determine the capillary properties of naturally occurring rock materials by a method such as the one used by Leverett. Core samples of natural materials are necessarily small and are not available in continuous sections of sufficient length for study by the simple drainage method. Therefore, other means of measuring capillary pressure have been devised. Essentially five methods of measuring capillary pressure on small core samples are used. These five methods are: (1) the desaturation or displacement process through a porous diaphragm or membrane (the restored state method of Welge), (2) the centrifuge or centrifugal method, (3) the dynamic capillary-pressure method, (4) the mercury-injection method, and (5) the evaporation method.

Natural petroleum reservoir rocks contain voids having capillary dimensions. The finer the pores of a rock are, the more important become the inherent capillary forces. Therefore, capillary pressure data contribute considerably towards evaluating reservoir rocks having low permeabilities. From these curves conclusions can be drawn regarding the pore structure, the saturation relationships, and the conditions of flow of the various reservoir fluids.

The mercury injection method of W.R. Purcell has proved especially suitable for measuring capillary pressure curves on core samples having low permeability. Compared to the restored state technique which requires the use of a semipermeable membrane, the procedure of Purcell offers the advantages of being less time-consuming and allowing measurement of a greater range of capillary pressures. However, difficulties can be encountered when converting the measured capillary pressure data obtained by mercury injection to values which are representative of the behavior using reservoir fluids.

It has been shown that even if the permeability of two rocks is the same, the rocks give pronounced differences in capillary pressure data, which can be explained from the pore size distribution curves of these rocks.

A review of the literature reveals that an additional problem exists concerning the application of capillary pressure data to the reservoir.

M. Muskat¹⁶ mentions, in regard to oil reservoirs, that the water content found above the transition zone is often higher than would be expected from capillary pressure measurements.

On the other hand, J.D. Duren⁷ reports water saturations that are lower than the corresponding capillary pressure data for a gas field.

Obviously these facts present a difficult problem which, among other things, can be attributed to hysteresis phenomena and the lack of knowledge of the values for interfacial tension and wettability, which are frequently unknown under reservoir conditions. A partial solution to this problem may be obtained if the effects of reservoir pressure and temperature are taken into account.

E. Hough et al ¹¹, measured the interfacial tension between water and methane up to high pressures and temperatures. According to these published data, much lower values for interfacial tension are obtained under reservoir conditions than under the conditions at which capillary pressure measurements normally are made, when only pressure differences are simulated.

Therefore, it seems that a good correlation between the capillary pressure measurements and the reservoir saturation can be obtained only by making allowance for the difference between the values of interfacial tension under laboratory and reservoir conditions.

The specific problem that confronts the gas industry is being able to predict how much 'over-pressure' a gas reservoir can withstand before leakage occurs by gas displacing water from the caprock overlying the reservoir. This is of economic importance since the storage capacity of a gas reservoir is proportional to its pressure.

It has been shown ²⁷ that Purcell's work suggests a means of correlating air-water and mercury threshold pressures of porous media.

Purcell and Burdine et al ⁵, both have reported on the computation of permeability from capillary pressure data obtained by the mercury-penetration method. Purcell utilized the concept of pore-size distribution without evaluating the distributions. He applied the data directly to the computation of permeability.

Burdine et al reported pore-size distributions as well as the results of the computation of permeability. They adapted the method of Ritter and Drake ²⁰ to the determination of pore-size distribution of reservoir rocks, and calculated permeability from this distribution.

In 1952 Brooks and Purcell ³ also reported a method for

measuring surface area on sedimentary rocks using mercury capillary pressure data.

Intuitively, it appears that the diaphragm method (the restored state) is superior in that oil and water can be used, thereby more nearly approaching actual wetting conditions. Hence, the diaphragm method is used as the standard against which all other methods are compared.

If the capillary properties determined by the diaphragm and mercury-injection methods are compared, it will be noted that the pressure scale for the curves determined by mercury injection is greater by a factor of 5 than that for the curves determined by the drainage of water displaced by air in a displacement cell. Purcell assumed that the contact angle for mercury against the rock surfaces was 140° and that of water was 0° .

By analogy to capillary tubes, the ratio of mercury capillary pressure to water-air capillary pressure is

$$\frac{P_{cm}}{P_{cw}} = \frac{\delta_m \cos 140^\circ}{\delta_w \cos 0^\circ} \quad (1)$$

Taking δ_m = surface tension of mercury = 480 dynes/cm.

δ_w = surface tension of water = 70 dynes/cm.

the preceding ratio is:

$$\frac{P_{cm}}{P_{cw}} = 5 \quad (2)$$

The agreement of the data when corrected by this ratio is close.

Purcell's mercury injection method offers the following advantages over other methods of determining capillary pressure data:

1. An entire capillary pressure curve consisting of as many as 20 to 30 points can be determined in a matter of hours rather than weeks.
2. Small, irregularly-shaped pieces such as drill cuttings can be handled in exactly the same manner as larger, regularly-shaped samples such as cores or permeability plugs.
3. The range of capillary pressures which can be observed is 5 to 10 times that of conventional methods.
4. A combination of the method for measuring the capillary pressure curve of drill cuttings and the equation relating permeability to the capillary pressure curve so determined makes possible the estimation of the permeability of those cuttings.

A favorable agreement of centrifuge data with data from the diaphragm method was reported by Slobod²³. A complete curve can be established in a few hours. The centrifuge method requires the same amount of time as the mercury injection method to obtain a capillary pressure curve, but the mercury injection equipment is much simpler to operate and is less expensive than the centrifuge equipment. The only disadvantages of the mercury injection method compared to the centrifuge method are the differences in wetting properties and in permanent loss of the core samples.

P A R T I
MANUAL ACQUISITION AND REDUCTION OF
DATA FROM PURCELL CELL

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DETERMINATION OF ROCK PROPERTIES

The nine core specimens used in this study were clean, homogeneous sandstone.

All cores were cut with a 1-inch interior diameter diamond core barrel using water, at right angles to the main axis of 3-1/2-inch standard oilfield cores. This was done to assure that the core samples used had their main axis generally parallel to any bedding planes that may have been present in the cored formation.

The cores were faced down to a fairly uniform size of approximately 1 inch in length. The residual fluids from each core were extracted using toluene in the modified ASTM extraction apparatus. Extraction was continued until the dry weight of a core remained constant between successive runs.

Bulk volumes were determined by the mercury displacement method. The porosity of each of the clean dry cores was then determined by the Stevens ²⁴ porosimeter, and the permeability by the conventional gas permeameter.

Porosity

Stevens porosimeter is a means of measuring the "effective" grain volume. The porosimeter consists of a core chamber which can be sealed from atmospheric pressure and closed off from the remaining parts of the porosimeter by a needle valve. The volume of the core chamber is known accurately. In operation the core is placed in the core chamber, and a vacuum is established in the system by manipulating the mercury reservoir; the air in the core and chamber is expanded into the evacuated

system and then measured at atmospheric pressure in the graduated tube. The difference in volume of the core chamber and of the air extracted is the "effective" grain volume, the volume of the grains plus any sealed pore space. Thus, if the effective grain volume is subtracted from the bulk volume, the volume of interconnected or effective pore space is obtained.

The following procedure was followed in determining grain volume by gas expansion using a Stevens-type porosimeter.

Volume of core chamber	=	A	c c
Volume of air (1st reading)	=	a	c c
Volume of air (2nd reading)	=	b	c c
Volume of air (3rd reading)	=	0	c c
Total of readings (a + b)	=	B	c c
Effective grain volume = A - B	=	D	c c
Bulk volume of sample (by mercury displacement method)	=	E	c c
Effective Porosity	=	$\frac{E - D}{E} \times 100$ percent	

Permeability

The absolute permeability of a core sample is determined from flow test data obtained by the conventional permeameter. A gas (usually air) is used as the flowing fluid for several reasons: (1) steady state flow is quickly obtained, which allows rapid determination; (2) dry air does not alter the mineral constituents of the rock; (3) 100 percent saturation to the flowing fluid is easily obtained. In this work nitrogen gas was used as the flowing fluid. The core was placed in a suitable holder which sealed the sides preventing by-passing of the core. The pressure differential was measured by suitable manometers, and the flow volume was obtained from a gas (wet test) meter.

Gas permeability is calculated from the suitable form of Darcy's equation ⁸.

For linear flow test:

$$K = \frac{q_m \mu L}{A \Delta P} \quad (3)$$

where

K = permeability, Darcys

q_m = flow rate at mean conditions, $\frac{P_1 + P_2}{2}$
cc /sec

μ = gas viscosity at test temperature, c p

L = sample length, cm

A = sample cross-sectional area, cm²

ΔP = pressure differential across sample, atm

P_1 = inlet pressure, atm (absolute)

P_2 = exit pressure, atm (absolute)

In order to obtain the absolute permeability of a rock from gas flow tests, it is necessary that an anomaly caused by the nature of a gas be accounted for. This was first recognized by Klinkenberg¹² and is known as the Klinkenberg effect or correction. This principle states that permeability to gas is a function of the mean free path of the molecules, and is, therefore, dependent on the mean pressure at which the test is performed. This is expressed by the equation

$$K_a = K \left(1 + \frac{b}{\bar{P}} \right) \quad (4)$$

where

K_a = the measured air permeability at pressure P

K = the true or absolute permeability of the rock
(also called equivalent liquid permeability)

b = a constant primarily dependent on pore size
(hence on permeability), which increases in
value as pore size decreases

$\bar{P}$ = mean pressure at which test is conducted

It is apparent that as P becomes large $K_a \rightarrow K$. This is the basis
for making the Klinkenberg correction. Gas permeabilities are measured
at several values of P and a plot of K_a vs $\frac{1}{P}$ is made. Extrapolation
to $1/P = 0$ ($P = \infty$) yields the true or equivalent liquid value K .

PRINCIPLE OF OPERATION OF THE PURCELL CELL

The Purcells manually-operated equipment¹⁸ consists of a fixed volume cell, having a window above and below it, mounted on a mercury pump. The pump is calibrated so that one turn of the hand wheel injects 1 c c into the cell. The scale on the wheel is marked in 0.01 c c divisions.

A dried and extracted core sample is weighed and placed in the cell. The cell is sealed and evacuated to about 5 microns or better, and mercury is brought up to a mark in the lower window by turning the hand wheel. The position on the hand wheel is noted and the mercury is then injected into the cell until it reaches the mark in the upper window.

By subtracting this volume of injected mercury from the known volume of mercury required to fill the empty cell, the bulk volume of the sample is obtained.

The air is next allowed to bleed into the system above the mercury. When the air pressure exceeds some minimum value, mercury is forced into the larger pores of the core, and the mercury level drops in the upper window.

When the mercury stops entering the pores at a given pressure, the hand wheel is rotated and enough mercury is injected into the cell to bring the level back to the mark on the upper window.

The volume of mercury injected is noted for each pressure increase. After air pressure on the mercury has been raised in steps to atmospheric, nitrogen gas from a cylinder is used to further increase the pressure to something over 1000 psia and to a maximum of 1500 psia.

This procedure of raising the pressure, waiting for the mercury

to stop entering the pores, and noting the amount of mercury required to maintain the level in the upper window is repeated for each point on the capillary pressure curve.

It is necessary to make blank runs with no sample in the cell to determine how much mercury is required to offset the cell expansion and mercury compression for each pressure change. The difference between the injected mercury and the blank is the amount of mercury injected into the sample.

Determination of Permeability from Capillary Pressure Data

W. R. Purcell developed an equation for the calculation of permeability using the mercury capillary pressure data. The equation which he put forward was:

$$K = FK_c \quad (5)$$

where

$$K_c = 0.66f I \quad (6)$$

$$I = \int_{\rho=0}^{\rho=100} \frac{d\rho}{(P_c)^2} \quad (7)$$

K = true permeability, m d

ρ = percent of total pore volume occupied
by the mercury

P_c = capillary pressure, atm

f = percent porosity

K_c = apparent permeability

F = the factor required to make true and
apparent permeabilities identical (lithology factor)

The value of the integral I, equation (7), is determined by plotting ρ vs $1/(P_c)^2$ and finding the area under this curve.

By putting in the value of the integral I and f (percent porosity) in equation (6) the value of the apparent permeability (K_c) is obtained.

The factor F is then obtained by dividing the true permeability (K) by the apparent permeability (K_c), where the true permeability is the permeability obtained by using a conventional permeameter and applying the Klinkenberg correction.

An average is then obtained of the lithology factors F calculated for different cores and this value of F is then used in equation (5) to calculate the permeability of every other core having nearly the same lithology.

In the plot ρ vs $1/(P_c)^2$, if ρ is plotted in fraction pore volume occupied by mercury instead of percent pore volume occupied by mercury, and if the porosity used in equation (5) is in fraction instead of percent, then equation (5) reduces to

$$K = 0.66fF \int_{\rho=0}^{\rho=1.0} \frac{d\rho}{(P_c)^2} 10^4 \text{ m d} \quad (8)$$

It should be noted that in the calculation of permeability by equation (5) from mercury capillary pressure data a surface tension of 480 dynes per cm and a contact angle of 140° were assumed by Purcell.

DETERMINATION OF PERMEABILITY USING DATA
FROM MANUALLY-OPERATED PURCELL CELL

The manually operated Purcell cell was used to determine the permeabilities of the cores by Purcell's approach. The values of the parameters were obtained by reading the pressure gauges and the scale on the mercury pump.

Calculations to obtain $1/P^2$ and ρ (fraction of pore volume filled with mercury) were done on the computer to obtain more accuracy and the graphs of $1/P^2$ vs ρ were plotted by hand. The areas under the curves were obtained by using a planimeter. The first five cores in this case were used to calculate the lithology factors, the average of which was used to calculate the permeabilities of the other four cores.

The results are presented in Appendix II.

P A R T I I

ON-LINE ACQUISITION AND REDUCTION OF DATA
FROM PURCELL CELL BY MEANS OF IBM 1800 COMPUTER

ON-LINE ACQUISITION AND REDUCTION OF DATA
FROM PURCELL CELL BY IBM 1800 COMPUTER

General

The basic requirement for connecting the Purcell cell to the computer is that each parameter which is to be measured should give an electrical output. For this, transducers, which preferably give a D.C. voltage output, should be used. The computer uses the voltage output to evaluate the dimension of the parameter concerned provided the calibration factor is known. If the transducer gives an A.C. voltage output, then it has to be converted into D.C. voltage before it can be used by the computer.

In the Purcell cell the parameters to be measured are the volume of mercury injected into the core and the corresponding pressure. The volume of mercury injected can be determined by the amount of linear displacement of the plunger of the pump or by the number of rotations of the hand wheel. If the amount of linear displacement of the plunger is used to determine the volume of mercury injected, then a linear displacement transducer is required, and if the number of rotations of the hand wheel are used to determine the volume of mercury injected, then an angular displacement transducer would be required.

Although the latter would have given more accuracy than the former, it was not used because of the fact that the pump had considerable backlash, and the angular displacement transducer would have recorded some mercury injection in spite of the fact that no displacement of the plunger had taken place. For this reason, the linear displacement transducer was used which would record mercury injection only when

the plunger is displaced. The linear displacement transducer would give voltage output proportional to the linear displacement. Therefore, to convert the output voltage into cubic centimeters of mercury the transducer had to be calibrated.

Similarly the measurement of the pressure can be made by a pressure transducer which also gives an electrical output. The pressures to be measured are between 0 - 1500 psig. Since the absolute error in any reading taken by most transducers is given as a percentage of the full scale of the transducer used, it was decided to use three transducers with ranges 0 - 50 psia, 0 - 100 psia, and 0 - 1500 psia, so that the percentage error in any reading taken between the range 0 - 1500 psig is small. When deciding the make, type and ranges of the transducers to be used, accuracy and economy were the main deciding factors. The transducers selected were the ones which gave the accuracy required at minimal cost.

The next requirement was to have a computer program which would process the data from the experiment.

The function of the program would be to allow the operator of the equipment to specify when the output from the linear displacement and pressure transducers should be read by the computer. The program was developed in such a way that the operator could feed into the computer output from any one of the three pressure transducers, together with the corresponding output from the linear displacement transducer. After the output from the transducers has been read by the computer, the program converts these values into the engineering units and writes the cumulative volume of mercury injected in cubic centimeters and pressure in atmosphere on the file. After these data have been stored on the file,

the program converts the cumulative volume of mercury injected into a fraction of pore volume, calculates $1/(P_c)^2$ and writes the fraction of pore volume occupied by mercury and the values of $1/(P_c)^2$ on the same file but in a different location.

After the above data are on the file, another program reads the necessary data from the file and plots them on the plotter. For the calculation of permeability, the program plots $1/(P_c)^2$ vs ρ (fraction pore volume occupied by mercury) and then fits a best curve through these datum points by the least squares method and causes this curve to be plotted on the plotter. The program then integrates between the limits $\rho = 0$ and $\rho = 1$ the polynomial obtained by the least squares method. This integration gives the value of the integral

$$\int_{\rho=0}^{\rho=1.0} \frac{d\rho}{(P_c)^2} \quad (9)$$

Putting this value in equation (8) the calculated value of the permeability is obtained in m d. The value of the porosity (f) is read from a certain location on the file depending on the core being run.

The next step is to obtain the capillary pressure curve. This is done by another program controlled by the mainline program (PIC04) which plots the value of $P_c(\text{atm})$ vs ρ (fraction pore volume occupied by mercury) on the plotter and uses the least squares technique to calculate the coefficients of a fourth order polynomial which fits the data and then plots the polynomial curve on the same graph as the experimental data.

All the above operations are initiated by binary digital switches at the operator's end.

DESIGN AND CONSTRUCTION OF THE EQUIPMENT

Pressure Transducers

While selecting the pressure transducers the following things were kept in mind:

1. Accuracy
2. Over pressure limits
3. Operable temperature range
4. Resolution
5. Pressure and electrical connections of the transducers
6. Repeatability
7. Cost

After comparing the specifications and cost of about ten different makes of transducers, the following pressure transducers were selected:

Manufacturer: Consolidated Electrodynamics Corporation

Type: 4-356-0001 High Range

4-356-0002 Low Range

Pressure ranges used: 0 - 50 psia, 0 - 100 psia, 0 - 1500 psia

Specifications: In Appendix VIII

Linear Displacement Transducer

This transducer was selected after comparing the specifications and prices of five different makes. The following are the design features of the transducer used:

1. High resolution

2. Zero hysteresis
3. Linearity error less than 0.5 percent
4. Built-in carrier oscillator
5. Built-in phase-sensitive demodulator
6. D.C. input - D.C. output
7. No phasing problems
8. No harmonic and quadrature null problems
9. Easy to use

Manufacturer: Hewlett Packard

Model 24DCDT-3000

Specifications: In Appendix VIII

Power Supplies

1. For Pressure Transducers

Each transducer was hooked up with an independent D.C. power supply which was designed to operate primarily as a power supply for strain gauge applications. It is a solid state power supply whose design, construction and size permit extreme isolation from the ground and the A.C. power line - greater than 10,000 megohms to the ground or A.C. input and less than 1 Pf capacity from output terminals to the input power line. The use of an independent power supply for each strain gauge provides excellent isolation capabilities, and the failure of a single strain gauge will not disrupt the entire test setup.

Manufacturer: Hewlett Packard

Model: 801C

Specifications: In Appendix VIII

2. For Linear Displacement Transducer

The manufacturer of the linear displacement transducer recommends their model 6204B power supply. This power supply features low ripple and noise, and freedom from drift. The supply automatically regulates with respect to either the front or rear terminals according to where the load is attached.

Manufacturer : Hewlett Packard

Model : 6204B

Specifications: In Appendix VIII

Analog Input Hardware

Analog input hardware permits the IBM 1800 system to directly measure the performance of industrial processes in a real time environment. Hundreds of different analog signals, each wired to a different sensor or instrument, may be connected to a single IBM 1800 computer. Each analog signal originates in a transducer that senses a physical phenomenon such as temperature, pressure, or motion, and transduces or converts the phenomenon into an electrical signal. The magnitude of the analog signal is related to the magnitude of the physical phenomenon to be measured.

Each analog electrical signal is carried into the IBM 1800 by a pair of wires screwed to terminals on the back of one of the computer cabinets. Once inside the IBM 1800, the signal is wired through a multiplexer and into an analog to a digital converter (ADC). The ADC reads the signal and produces a bit pattern to represent the value of the signal voltage as a binary number. It does this in much the same way as a

card reader reads patterns of holes punched in cards and produces bit patterns to represent hole patterns. From a programming point of view, an ADC is just another input device, like a card reader or a paper tape reader.

Since the ADC is a relatively complex and expensive device, only one or two ADCs ordinarily do all the analog conversions for an entire IBM 1800 system, which may include hundreds of different analog signals. A multiplexer or switching device momentarily connects the desired signal lines to the ADC, the ADC then reads and converts the signals in a few microseconds and the multiplexer connects another signal to the ADC to be read. Two types of multiplexers are used: relay multiplexers that can switch up to a hundred different signals per second, and solid state multiplexers that can switch up to 20,000 signals per second through the ADC.

All the analog signals coming into the ADC must fall within a voltage range of plus or minus 5 volts. Low voltage signals in the millivolt ranges are amplified by electronic amplifiers located between the multiplexers and the ADC, so that many signals may share a single amplifier.

Analog signals relating the current level of the signals (instead of the voltage level) to the phenomenon to be measured may also be read by the IBM 1800 system. These signals are converted to voltage-signals before entering a multiplexer. Electrical noise filters may also be used to improve the signal to noise ratio.

Analog Input Subroutines

A family of three Fortran callable subroutines has been provided to control the many options involved in analog input. The subroutines are AIP, to read a single analog signal; AIS, to read a group of signals sequentially; and AIR, to read a group of signals in random sequence. The subroutine with which this work is concerned is AIP because a single analog signal at a time would have to be read in this work.

The general calling sequence of the AIP subroutine is

CALL AIP (I , J, K)

where I is an integer constant or expression that specifies various control options, J is the name of the variable that will receive the converted analog value, and K is an integer constant or expression that specifies the analog point multiplexer address to be read.

The parameter I in the calling sequence has a value of five decimal digits, and each digit specifies a different control option. The high-order (ten-thousandths) digit specifies the ADC resolution to be used during conversion: zero specifies 11-bit resolution, one specifies 14-bit resolution, and two specifies 8-bit resolution. The thousandths digit contains a zero or one to specify whether the ADC should be tested to see if it is busy or should be read. If the ADC is to be tested, the second (J) parameter is set to a value of one if busy, and two if not busy. The third (K) parameter is not used with the test function. The hundredth digit of the parameter I specifies external synchronization: one if yes, zero if no. The tens digit specifies which of two possible ADC's are to be used: zero for the first ADC, one for the second. The low order or units digit must be zero.

As an example, consider the calling sequence

CALL AIP (11000, IPRES, 120)

which specifies that 14-bit resolution is to be used to read an analog signal from the first ADC without external synchronization. The signal is to be read from a relay multiplexer wired to analog point number 120, and the converted reading is to be stored in the variable named IPRES.

If the ADC is to be tested to see if it is busy, the calling sequence is

CALL AIP(00000, ITEST)

which specifies that the ADC should be tested. If the ADC is busy, ITEST is set to one; and if not busy, it is set to two.

Calibration of the Transducers

Pressure Transducers

1. Range 0 - 50 psia

The output from this transducer at 50 psia is 40 mv. The maximum digital value that can be obtained from the ADC with 14-bit resolution is 32767 when the input is 50 mv. So the digital value that we will get when the input is 40 mv will be

$$\left(\frac{32767}{50}\right)40 = 26214$$

i.e. when the pressure is 50 psia the digital value obtained from the ADC will be 26214. So the following calibration equation will give the pressure in psia

$$\text{Pressure} = (50.0/26214) \text{IPRES psia}$$

where IPRES will receive its value from the calling sequence

CALL AIP (11000,IPRES,120) in which number 120 is the analog point number to which this transducer is connected.

2. Range 0 - 100 psia

In this case the calibration equation is

$$\text{Pressure} = (100.0/26214)\text{IPRES psia}$$

since the output from the transducer at 100 psia is 40 mv. The IPRES will receive its value from the calling sequence,

CALL AIP(11000,IPRES,121)

in which number 121 is the analog point number to which this transducer is connected.

3. Range 0 - 1500 psia

In this case the calibration equation is

$$\text{Pressure} = (1500/26214)\text{IPRES psia}$$

since the output from the transducer at 1500 psia is 40 mv. The IPRES will receive its value from the calling sequence

CALL AIP(11000,IPRES,122)

in which number 122 is the analog point number to which this transducer is connected. The calibration curves are presented in Appendix IX.

Linear Displacement Transducer

The full scale output from this transducer is 13 vdc which cannot be fed directly into the computer. As mentioned earlier, all the analog signals coming into the ADC must fall within a voltage range of plus or minus five volts. For this reason a resistor was used to reduce the full scale output from the transducer so that it was less than five volts. It was also mentioned that 0.1 cm movement of the plunger of the mercury pump injected 1 c c of mercury into the cell and the movement of the pump can be read up to 0.001 c c or better on the wheel scale.

To calibrate the transducer, the amount of mercury injected into the cell at different positions of the plunger of the mercury pump and the corresponding digital values from the computer (ADC) are noted. These points are plotted on a large graph paper for accuracy and a best straight line is passed through these points.

The calibration equation for this transducer is

$$\text{Volume Injected} = (46.1/32767) \text{IVOL} \text{ c c}$$

IVOL will receive its value from the calling sequence

CALL AIP(11000,IVOL,47)

in which 47 is the analog point number to which this transducer is connected. The calibration curve is presented in Appendix IX.

It should be noted that the analog points in the computer to which the pressure transducers are connected can take a maximum voltage of 50 mv at which the digital value from the ADC would be 32767, and the linear displacement transducer is connected to the analog point which can take a maximum voltage of 5 volts at which the digital value from the ADC would be 32767.

Subroutines Used in the Main Line Program

DOUT1

is a digital subroutine which allows the user to test or set a digital output bit using a logical group address. The calling sequence is as follows:

CALL DOUT1 (I,J,K)

where

I = control-parameter bit number (1-16) to be set

J = logical group address

K = bit status - 1 bit ON, 0 bit OFF

This subroutine is used to turn the red light on when the Main Line Program is queued and to turn it off when this program has been executed. To know that the program has been executed is important because the next values of the pressure and volume of mercury injected cannot be read by the computer unless the previous values have been registered. In this work the calling sequence is

CALL DOUT1 (4,15,1) to turn the light ON

CALL DOUT1 (4,15,0) to turn it OFF

DIGIN

This subroutine reads a digital input group and converts a specified sequence of bits into a binary number. The calling sequence is as follows:

CALL DIGIN(IADDR,ISTRT,LNGTH,IVLUE)

where

IADDR = Address of digital input group

ISTRT = First bit in the desired sequence (0 - 15)

LNGTH = Number of bits in the sequence (1 - 16)

IVLUE = Equivalent binary value returned

In this work the calling sequence is

CALL DIGIN (069,0,4,IVLUE)

CALL QUEUE

This statement is used to place a main line core load name and priority in the queue. If the same name and priority are already queued, they will not be placed in the queue a second time. However, the same name with different priority can be inserted into the queue. The format of the statement is CALL QUEUE(NAME,P,E)

where

NAME is the name of a main line core load that is to be entered into the queue.

P is the integer expression that specifies the execution priority for the core load. One is the highest priority number. The allowable range of P is from 1 to 32767.

E is an error parameter used to specify the action to be taken when the queue is full. E = 0 Ignore call after printing an error message. E = 1 through 32766. Replace the lowest priority entry in the queue with the name and priority in this call, if the priority of the queue entry is lower (numerically larger) than E. If there is no queue entry with a lower priority, the restart core load specified for this core load is executed.

E = 32767 Execute restart core load. Different core loads can be assigned the same priority number if desired. When two or more queue entries have been assigned the same priority, these entries have a priority among themselves on a first in, first out basis. The CALL QUEUE statement can be used in any program.

In this work the CALL QUEUE statements are

```
CALL QUEUE(MAHMD,32767,0)
```

```
CALL QUEUE(CHAUD,32767,0)
```

where MAHMD and CHAUD are the main line core load names.

CALL CHAIN(NAME)

This call in a main line core load transfers control to the PSC (program sequence control program) which loads the named main line core load into core storage for operation. This is the last logical statement in a section of a main line core load. It calls the next part of the main line core load into operation.

NAME is the name of the main line core load being called.

Procedure for Running the Equipment

The flow chart of the equipment is as shown in Figures 1, 2, and 3. A dried and extracted core sample is placed in the cell. All the valves are closed except 2, 3, and 10 in Figure 1. The cell is evacuated to about 5 microns and mercury is brought up to a mark in the lower window by turning the hand wheel. Then valve 2 is closed. The position of the binary digital switches is set at 6 and the interrupt switch is pressed to queue the mainline core load PIC04. The red light goes on as soon as the PIC04 core load is queued. The position of the binary digital switches is read by DIGIN which returns an equivalent value to IVLUE in the computed "GO TO" statement in the main line program (PIC04). The computed "GO TO" statement causes the statement number 105 to be executed (since the binary digital switches are set at 6) which writes "1" in location (1) on file 87. Statement number 450 is then executed which turns off the red light.

That the red light goes "ON" and "OFF" each time the interrupt switch is pressed is important because unless the first operation is complete the next one cannot be started. When the red light goes off we know for sure that the required operation has been completed.

The position of the binary digital switches is then set to 1 and the interrupt switch is pressed. The red light goes on as soon as the PIC04 core load is queued. The position of the binary digital switches is read by DIGIN which returns an equivalent value to IVLUE in the computed "GO TO" statement in the main line program (PIC04). The computed "GO TO" statement causes the statement number 100 (since the binary digital switches are set at 1) to be executed, which causes the linear displacement transducer (L.D.T.) to be read. The reading after conversion to cubic centimeters of mercury is stored on file 88 in location number 1 which is read from file 87 location (1). After the linear displacement transducer (L.D.T.) is read and the reading written on file 88, the location in which the next reading is to be written is set to 2 and this is written on file 87 in location (1) from where it will be read before the next reading is written on file 88. After this the red light is turned off by statement 450.

The mercury is then injected into the cell until it reaches the mark in the upper window. The binary switches are set to 1 and the interrupt switch is pressed. The light goes on and the position of the binary switches is read by DIGIN and statement number 100 is executed, which causes the L.D.T. to be read and the reading in cubic centimeters of mercury to be written on file 88 in location (2) which is read from location (1) on file 87.

The location in which the next reading is to be written on file 88 is set to 3 and is written on file 87 location (1) from where it will be read before the next reading is written on file 88. After this the red light is turned off by statement number 450.

The air is next allowed to bleed into the system above the

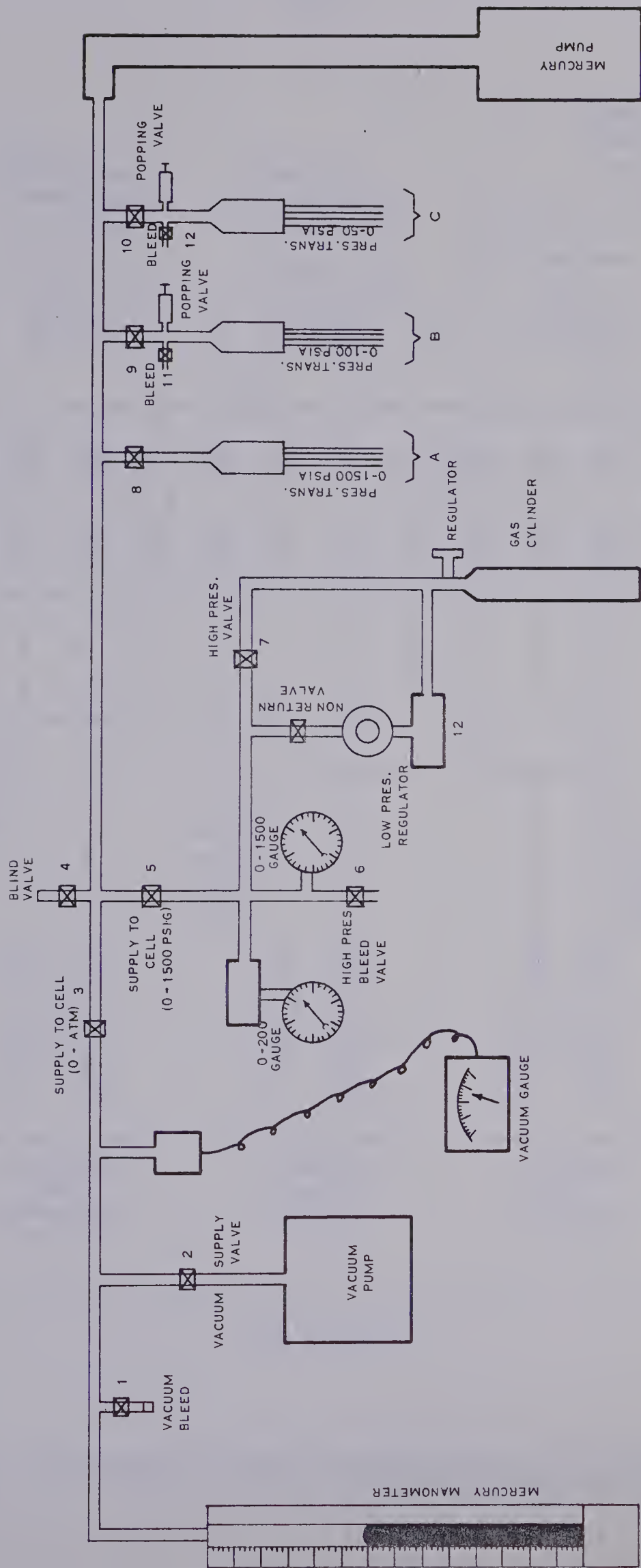


Figure 1. MERCURY CAPILLARY PRESSURE APPARATUS.

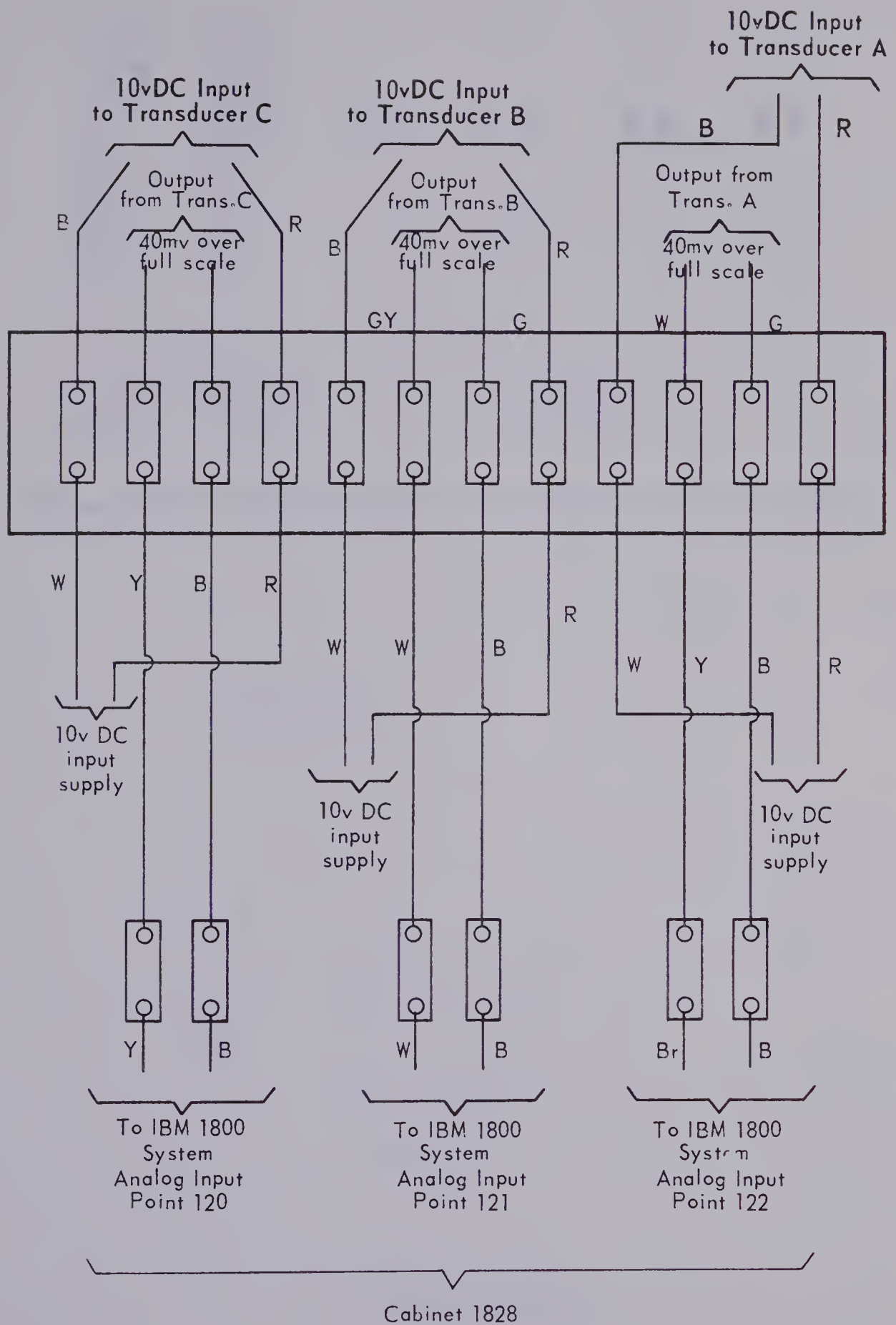


Figure 2. ELECTRICAL CIRCUIT FOR PRESSURE TRANSDUCERS

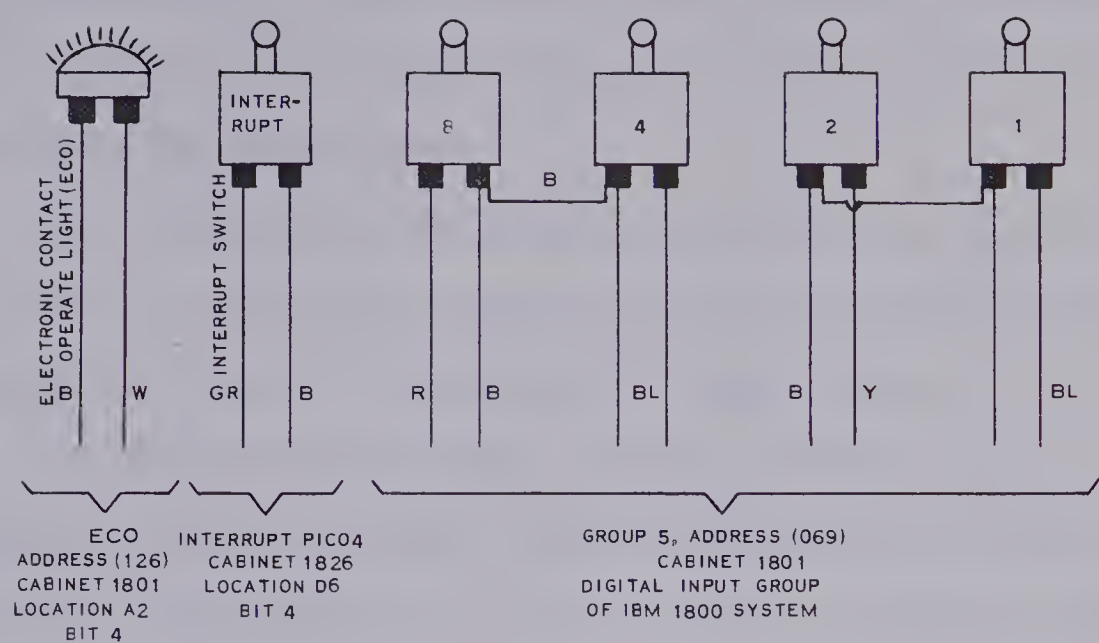


Figure 3(a) ELECTRICAL CIRCUIT FOR BINARY DIGITAL SWITCHES.

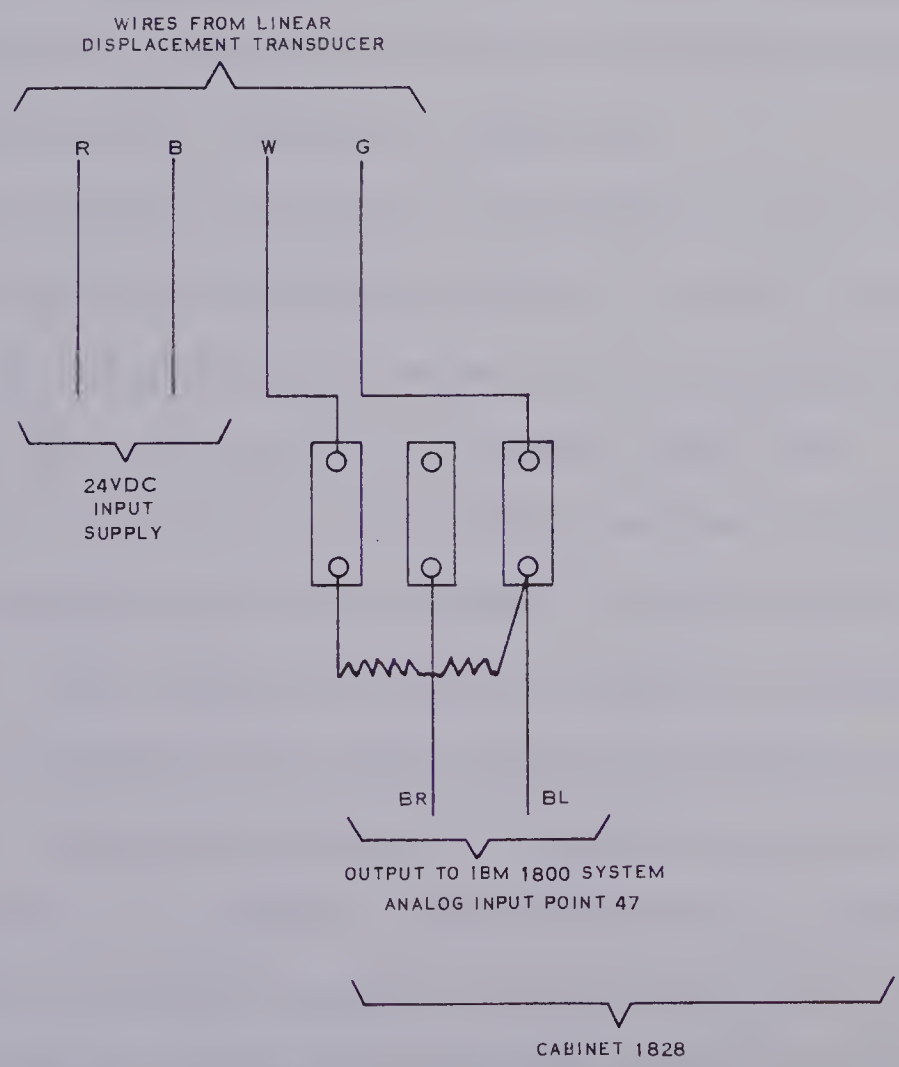


Figure 3(b) ELECTRICAL CIRCUIT FOR LINEAR DISPLACEMENT TRANSDUCER.

mercury from valve (1). When the air pressure exceeds some minimum value, mercury is forced into the larger pores of the core, and the mercury level drops in the upper window.

When the mercury stops entering the pores at a given pressure, the hand wheel is rotated and enough mercury is injected into the cell to bring the level back to the mark on the upper window.

The position of the binary digital switches is set to 2 and the interrupt switch is pressed. The red light goes on and the position of the binary digital switches is read by DIGIN and statement number 101 is executed, which causes the L.D.T. and pressure transducer (P.T.) (0 - 50 psia) to be read. The L.D.T. reading in location (2) on file 88 is subtracted from this L.D.T. reading, and the resulting value which is the volume of mercury injected into the core in cubic centimeters, along with the pressure in atmospheres, is written on file 88 in location (3), which is read from the location (1) on file 87.

The location in which the next reading is to be written on file 88 is set to 4 and is written on file 87 location (1) from where it will be read before the next reading is written on file 88. After this the red light is turned off by statement number 450.

After air pressure on the mercury has been raised in steps to atmospheric, nitrogen gas from a cylinder is used to further increase the pressure. This is done by closing the valve (3) and applying pressure from the nitrogen cylinder and regulating it through the low pressure regulator. When the pressure to be applied to the cell has been regulated, valve (5) is opened to supply the pressure to the cell.

When the pressure reaches 50 psia, valve (10) is closed and valve (9) is opened. To read the output from the L.D.T. and pressure

transducer (0 - 100 psia), the position of the binary digital switches is set to 3 and the rest of the procedure is the same.

When the pressure reaches 100 psia, valve (9) is closed and valve (8) is opened and the output from the L.D.T. and pressure transducer (0 - 1500 psia) is read by setting the position of the binary digital switches to 4. The rest of the procedure is the same as above.

It should be noted that when the pressure increases to 100 psig, valve (7) is to be opened because the low pressure regulator has a range from 0 - 100 psig and when the pressure increases to 100 psig, valve (12) closes automatically to protect the pressure regulator.

When the pressure and the corresponding values of the mercury injected are written on the file, the program "porosity" is run. It stores the values of the porosity of all the cores to be run on file 87, starting from location (3).

The position of the binary digital switches is then set to 6 and the interrupt switch is pressed which executes the statement number 105 which stores number 1 in location (1) on file 87. Then the position of the binary digital switches is set to 9 and the interrupt switch is pressed which executes statement number 108, which reads the number in location (1) of file 87 and increments it by one and writes it back on file 87 in location (1). This process of incrementing the number by one can be continued by simply pressing the interrupt switch with the position of the binary digital switches set to 9. When the number stored in location (1) on file 87 is the same as the number of the core being run, the position of the binary digital switches is set to 5 and the interrupt switch is pressed. The red light goes on and the position of the binary digital switches is read by DIGIN and statement number 104 is executed,

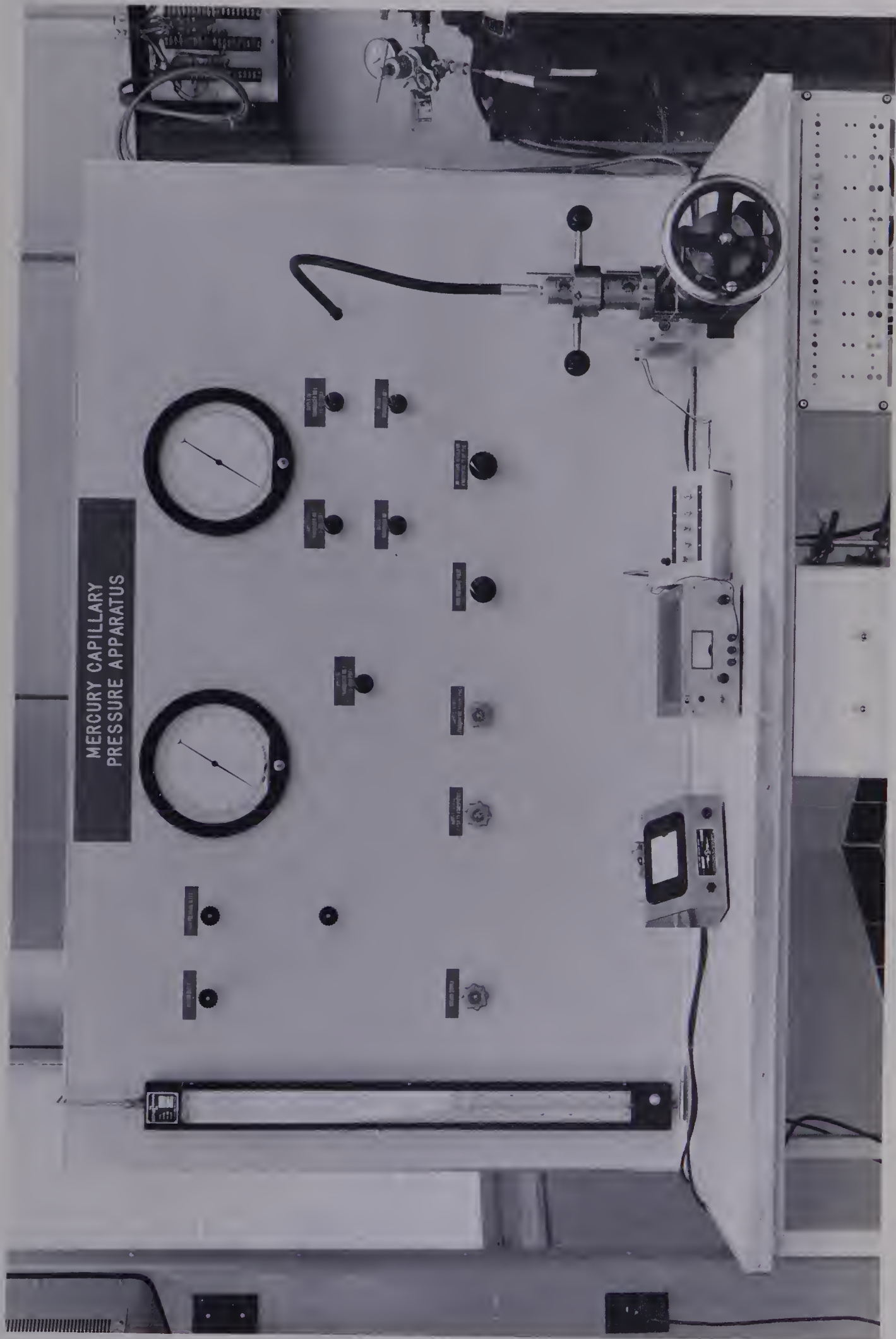


Figure 4. MERCURY CAPILLARY PRESSURE APPARATUS (Front View)

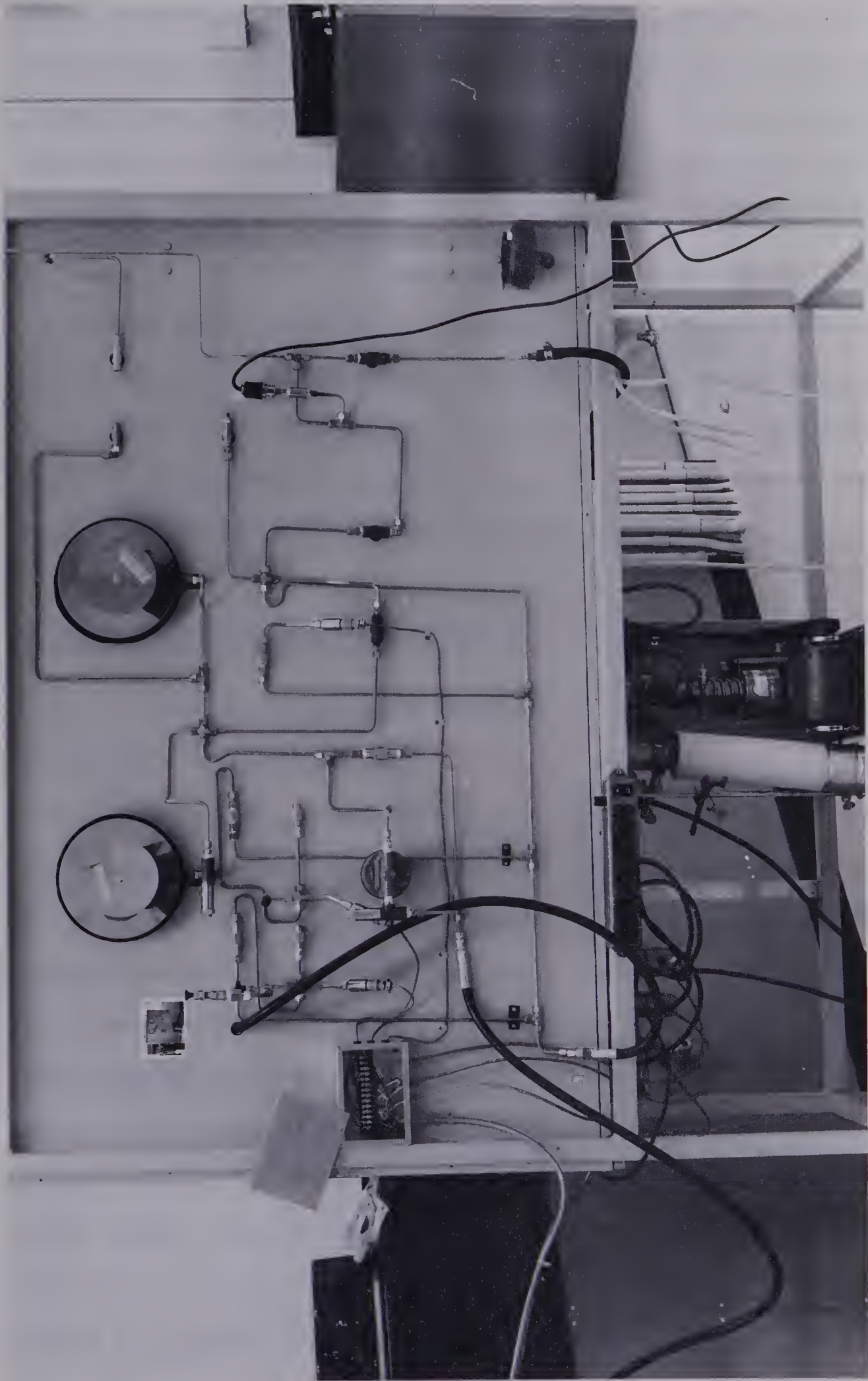


Figure 5. MERCURY CAPILLARY PRESSURE APPARATUS (Rear View).

which reads the values stored in location (1) and location (2) by the linear displacement transducer on file 88. By subtraction, the bulk volume of the core is found in cubic centimeters. Then the number stored in location (1) of the file 87 is read. This number was set equal to the number of the core being run, and is utilized to read the porosity of that core. From the porosity and the bulk volume, the pore volume of the core is determined which is required to calculate the fraction of pore volume filled with mercury. The pressure in atmospheres is used for calculating the $1/P^2$ values. Then all the above data are stored on file 88. These data are then printed out in a tabular form on the IBM 1132 printer. Then the statement 450 turns the light off.

Determination of Permeability (Calculated) From On Line-Purcell Cell

In order to determine the apparent permeability of the core, the position of the binary digital switches is set to 7 and the interrupt switch is pressed which executes statement number 106 and queues the mainline core load named CHAUD. This specifies the control parameters for plotting subroutines, and then calls CHAIN (RNPLT) which transfers control to the core load named RNPLT, which plots the X and Y axis with the labels and plots the data from file 88. The reciprocal of pressure (atm) squared is plotted versus the fraction of pore volume filled with mercury. The scale is automatically adjusted between the maximum and minimum values of each vector. After plotting the data points, the CALL CHAIN (STAND) statement transfers control to the core load named STAND which fits the best curve through the data points by the least squares method to a maximum of a fourth degree polynomial, and all the data of the least square fit are printed out on the IBM 1132 printer. The

polynomial obtained from the best fit is integrated between the limits 0 and the maximum value of the ρ vector. This gives the area under the curve between the specified limits and it gives the value of the integral $\int_{\rho=0}^{\rho=\max} \frac{d \rho}{(P_c)^2}$. This value of the integral is written on file 87 location (2).

The number on file 87 location (1) is set equal to the number of the core being run, the procedure being the same as explained earlier. The position of the binary digital switches is then set at 10 and the interrupt switch is pressed which turns on the red light and executes the statement number 109. This reads the value of the area under the curve from file 87 location (2) and then reads the value of the porosity of the core from file 87 and location (X) corresponding to the number in location (1) of file 87. After reading these values, the permeability is calculated using equation

$$K = 0.66f \int_{\rho=0}^{\rho=\max} \frac{d \rho}{(P_c)^2} \quad (10)$$

The apparent permeability, porosity, and the area under the curve are then printed on the IBM 1132 printer.

Capillary Pressure Curve

To obtain the capillary pressure curve, the position of the binary digital switches is set to 8 and the interrupt switch is pressed which executes statement number 107 and queues the mainline core load named MAIMD which specifies the control parameters for the plotting subroutine and then calls CHAIN(CMPLT) which transfers control to the core

load named CMPLT which plots the X and Y axis with the labels and plots the data points from file 88. The fraction of pore volume filled with mercury (ρ) for each data point is plotted on the X-axis and the pressure in atmospheres is plotted on the Y-axis. The scale is automatically adjusted between the minimum and maximum values of each vector. After plotting the data points, the CALL CHAIN (STILL) statement transfers control to the core load named STILL which fits the best curve through the data points by the least squares method to a maximum of a fourth degree polynomial. All the data of the least square fit is printed out on the IBM 1132 printer.

Determination of Permeability Using On Line Purcell Cell

The on line mercury capillary pressure apparatus was used for the determination of permeability (calculated) using Purcell's approach, the procedure being as explained earlier.

The first five cores were used to determine the lithology factors, the average of which was used to determine the permeabilities of the cores 6 through 9 using the Purcell's approach. The results are presented in Appendix IV.

Determination of Capillary Pressure Curve

The capillary pressure curves of all the nine core specimens were obtained using the on-line Purcell cell. The procedure being the same as explained earlier. The results are presented in Appendix IV.

RESULTS AND CONCLUSIONS

The Purcell cell has been successfully connected to the IBM 1800 computer and the usefulness of this approach demonstrated. Experimental results are discussed in Appendix X.

The permeabilities obtained by the use of the on-line Purcell cell were observed to have lower standard deviation than the permeabilities obtained by the use of manually-operated equipment. The reason for this being that the permeability was very sensitive to the value of the area under the curve used. The values of the areas under the curves obtained by the use of the on-line equipment were more accurate than the values obtained by using a planimeter. The values of the pressure, and volume of mercury injected are also determined more accurately by the use of the on-line equipment because it used calibration curves which smoothen the data and eliminates personnel errors. The use of absolute pressure transducer takes into account the day to day change in atmospheric pressure and eliminates errors like the one caused by switching from the barometer to the pressure gauge.

The time required to obtain the permeability by the use of on-line equipment was reduced to one-sixth the time required to obtain the permeability by the use of manually-operated equipment after the system was operating.

Although the time required to obtain the permeability from on-line equipment is the same as for the conventional permeameter, even then the on-line equipment has the advantage that in addition to permeability, it gives a capillary pressure curve, and it could also be used for determining the permeabilities of drill cuttings.

By using Thomeer's²⁵ technique it was not possible to fit a continuous curve through the data obtained from the cores used in this work. It was possible to fit two curves, one for data at low pressures and the other for data at high pressures. This may be due to dual pore size distribution in the cores.

The capillary pressure curve-fit presented in this work was not entirely satisfactory although it was the best fit possible by using the powers of x as basis functions.

Since the lithology of the core samples used was not very different it should be noted from Tables VII-1, VII-3 and IX-10 that the lithology factors do not vary much, and the position and shape of the capillary pressure curves in Figures IV-10 through IV-18 are quite similar, which shows the pore size distribution of the cores is not very different. The shape of the capillary pressure curves also show that most of the pore volume of the cores consist of large pores, in which mercury can be injected at low pressures.

The effect of expansion of the mercury cell and contraction of the mercury with pressure was taken into account for data obtained from the manually-operated Purcell cell. This corrected data is presented in Appendix IX. It was observed that by neglecting this effect, a maximum error of -1.05 percent was introduced in the calculation of the permeability (Table IX-11). It should be noted that an accuracy to a maximum of only three significant figures was obtained, although in the presentation of the data five to seven significant figures have been used.

RECOMMENDATIONS

This work has successfully demonstrated the feasibility of on-line acquisition and reduction of data from mercury capillary pressure apparatus. An attempt should now be made to obtain the pore size distribution curve by writing a program for this purpose. This pore size distribution can then also be used for evaluating the permeability of the core¹⁰.

The capillary pressure data can also be used for the determination of the surface area of the porous media³. This can be done by on-line data processing for this purpose.

A core-load can also be programmed for obtaining the family of capillary pressure curves for different values of pore geometrical factors²⁵.

NOMENCLATURE

A	cross sectional area (cm^2)
b	Klinkenberg factor
f	percent porosity
F	lithology factor
K	true or absolute permeability (darcys)
K_c	apparent permeability (darcys)
K_a	measured air permeability (darcys)
L	length (cm)
P_1	inlet pressure (atm)
P_2	exit pressure (atm)
ΔP	pressure differential (atm)
$\bar{P}$	mean pressure (atm)
P_c	capillary pressure (atm)
P_{cm}	mercury capillary pressure (atm)
P_{cw}	water capillary pressure (atm)
q_m	flow rate at mean conditions (cc / sec)
δ_m	surface tension of mercury (dynes/cm)
δ_w	surface tension of water (dynes/cm)
μ	viscosity (cp)
ρ	percent of total pore space occupied by mercury

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A P P E N D I X I

PERMEABILITY DATA FOR CORES 1 THROUGH 9

Table I-1
Core Properties

Core No.	Diameter cms	Length cms	Bulk Volume c c	Effective Porosity	Absolute Permeability m d
1	2.51	2.68	13.26	0.320	178.10
2	2.51	2.68	13.25	0.293	155.12
3	2.51	2.76	13.69	0.255	172.40
4	2.51	2.69	13.33	0.241	200.50
5	2.51	2.70	13.32	0.205	112.05
6	2.46	2.81	13.46	0.225	176.80
7	2.46	2.74	13.16	0.205	140.90
8	2.46	2.77	13.20	0.263	160.20
9	2.46	2.78	13.30	0.214	177.30

Table I-2
Permeability Data

Core 1

RUN	PRES. DROP ATM	FLOW RATE CC/SEC	MEAN CORE PRES. ATM	FLOW RATE AT MEAN PRES. CC/SEC	CAL. AIR PERM DARCYS	1/P ₁ ATM ⁻¹
1	0.6526	25.4880	1.2575	18.8739	0.2788	0.7952
2	0.8421	33.9840	1.3522	23.4022	0.2679	0.7395
3	1.0723	45.7840	1.4673	29.0542	0.2612	0.6814
4	1.3236	59.9439	1.5930	35.0395	0.2552	0.6277
5	1.6276	78.8240	1.7449	42.0628	0.2491	0.5730
6	1.8750	95.8160	1.8686	47.7460	0.2455	0.5351
7	2.2131	119.8879	2.0377	54.7844	0.2386	0.4907

Table I-3
Permeability Data

Core 2

RUN	PRES. DROP ATM	FLOW RATE CC/SEC	MEAN CORE PRES. ATM	FLOW RATE AT MEAN PRES. CC/SEC	CAL. AIR PERM DARCYS	1/P ATM ⁻¹
1	0.5921	25.9600	1.2272	19.6975	0.3207	0.8148
2	0.8052	36.3440	1.3338	25.3730	0.3038	0.7497
3	1.0184	47.6720	1.4403	30.8189	0.2918	0.6942
4	1.2750	64.1920	1.5686	38.1049	0.2881	0.6374
5	1.5039	76.9360	1.6831	42.5637	0.2729	0.5941
6	1.7368	92.9840	1.7996	48.1134	0.2671	0.5556
7	2.1157	119.8879	1.9890	56.1253	0.2557	0.5027

Table I-4
Permeability Data
Core 3

RUN	PRES. DROP ATM	FLOW RATE CC/SEC	MEAN CORE PRES. ATM	FLOW RATE AT MEAN PRES. CC/SEC	CAL. AIR PERM DARCYs	1/P ATM ⁻¹
1	0.7894	40.1200	1.3259	28.1759	0.3544	0.7541
2	0.9197	47.6720	1.3910	31.9121	0.3445	0.7188
3	1.1473	62.3040	1.5048	38.5525	0.3336	0.6645
4	1.3473	75.0480	1.6048	43.5446	0.3209	0.6231
5	1.4947	86.3760	1.6785	47.9174	0.3183	0.5957
6	1.7894	107.6160	1.8259	54.8820	0.3045	0.5476
7	2.0197	124.6080	1.9410	59.7783	0.2939	0.5151

Table I-5
Permeability Data

Core 4

RUN	PRES. DROP ATM	FLOW RATE CC/SEC	MEAN CORE PRES. ATM	FLOW RATE AT MEAN PRES. CC/SEC	CAL. AIR PERM DARCY	1/P ₁ ATM ⁻¹
1	0.8594	39.6480	1.3609	27.1283	0.3054	0.7347
2	1.0432	49.5600	1.4528	31.7652	0.2946	0.6883
3	1.2561	63.7200	1.5592	38.0529	0.2931	0.6413
4	1.4802	76.9360	1.6713	42.8653	0.2802	0.5983
5	1.6973	93.4560	1.7798	48.8939	0.2788	0.5618
6	1.9671	115.1679	1.9147	56.0090	0.2755	0.5222
7	2.0250	118.0000	1.9436	56.5316	0.2701	0.5144

Table I-6
Permeability Data
Core 5

RUN	PRES. DROP ATM	FLOW RATE CC/SEC	MEAN CORE PRES. ATM	FLOW RATE AT MEAN PRES. CC/SEC	CAL. AIR PERM DARCS	1/P ATM ⁻¹
1	0.6973	25.0160	1.2798	18.2007	0.2535	0.7813
2	0.9631	34.9279	1.4127	23.0218	0.2322	0.7078
3	1.2855	50.5039	1.5739	29.8793	0.2257	0.6353
4	1.6026	65.6080	1.7324	35.2629	0.2137	0.5772
5	1.8421	78.8240	1.8522	39.6275	0.2089	0.5398
6	2.0907	92.5119	1.9765	43.5832	0.2025	0.5059
7	2.4421	111.3920	2.1522	48.1947	0.1917	0.4646

Table 1-7
Permeability Data
Core 6

RUN	PRES. DROP ATM	FLOW RATE CC/SEC	MEAN CORE PRES. ATM	FLOW RATE AT MEAN PRES. CC/SEC	CAL. AIR PERM DARCYs	1/P ATM ⁻¹
1	0.7763	35.8720	1.3193	25.3182	0.3432	0.7579
2	1.0618	51.4480	1.4621	32.7661	0.3247	0.6839
3	1.2171	67.4960	1.5897	39.5356	0.3159	0.6290
4	1.5657	84.4880	1.7140	45.8986	0.3085	0.5834
5	1.8315	101.4800	1.8469	51.1629	0.2940	0.5414
6	2.1210	125.5520	1.9917	58.6993	0.2912	0.5020
7	2.2842	133.5760	2.0732	59.9934	0.2764	0.4823

Table I-8
Permeability Data

Core 7

RUN	PRES. DROP ATM	FLOW RATE CC/SEC	MEAN CORE PRES. ATM	FLOW RATE AT MEAN PRES. CC/SEC	CAL. AIR PERM DARCYs	1/P ATM ⁻¹
1	0.7460	26.4320	1.3042	18.8720	0.2596	0.7667
2	1.0355	38.7040	1.4489	24.8736	0.2465	0.6901
3	1.3026	51.4480	1.5825	30.2733	0.2385	0.6319
4	1.5421	64.1920	1.7022	35.1153	0.2337	0.5874
5	1.8000	77.8800	1.8311	39.6031	0.2258	0.5460
6	2.0500	91.5680	1.9561	43.5882	0.2182	0.5111
7	2.2105	101.4800	2.0364	46.4026	0.2154	0.4910

Table I-9
Permeability Data

Core 8

RUN	PRES. DROP ATM	FLOW RATE CC/SEC	MEAN CORE PRES. ATM	FLOW RATE AT MEAN PRES. CC/SEC	CAL. AIR PERM DARCYS	1/P ATM ⁻¹
1	0.7355	34.4560	1.2989	24.7006	0.3484	0.7698
2	0.9868	49.0879	1.4246	32.0860	0.3373	0.7019
3	1.2447	64.6640	1.5535	38.7589	0.3230	0.6436
4	1.5263	82.6000	1.6943	45.3956	0.3085	0.5901
5	1.7565	97.7040	1.8094	50.2800	0.2969	0.5526
6	2.0039	115.1679	1.9331	55.4753	0.2872	0.5172
7	2.2250	131.6880	2.0436	60.0023	0.2798	0.4893

Table I-10
Permeability Data
Core 9

RUN	PRES. DROP ATM	FLOW RATE CC/SEC	MEAN CORE PRES. ATM	FLOW RATE AT MEAN PRES. CC/SEC	CAL. AIR PERM DARCS	1/P-1 ATM
1	0.7263	30.6800	1.2943	22.0720	0.3164	0.7725
2	0.9973	45.3120	1.4298	29.5088	0.3080	0.6993
3	1.2618	59.9439	1.5621	35.7331	0.2948	0.6401
4	1.5486	76.9360	1.7055	42.0055	0.2824	0.5863
5	1.8197	95.8160	1.8410	48.4626	0.2773	0.5431
6	2.1026	115.6400	1.9824	54.3163	0.2690	0.5044
7	2.3671	135.4640	2.1147	59.6489	0.2624	0.4728

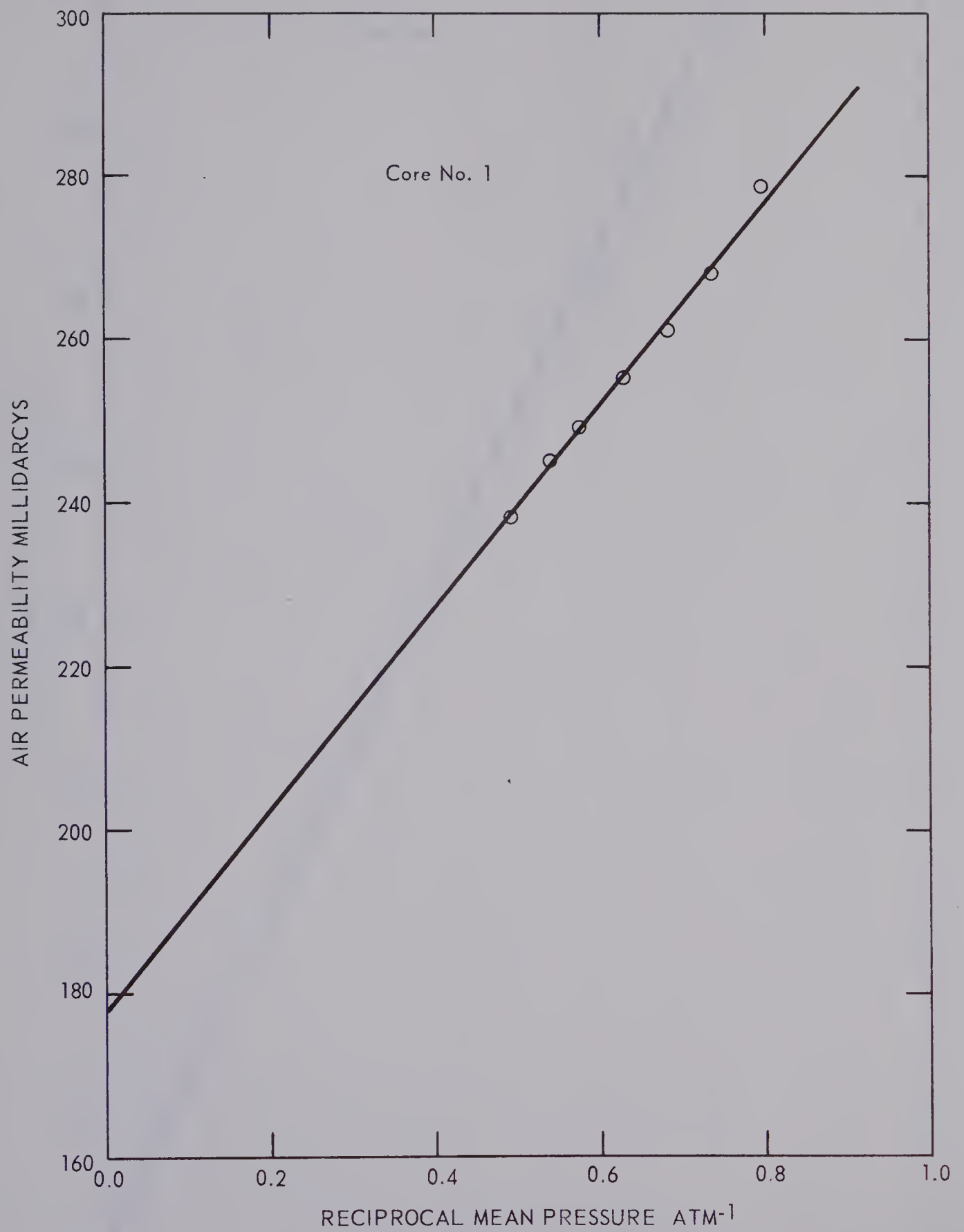


Figure I-1

KLINKENBERG CORRECTION PLOT

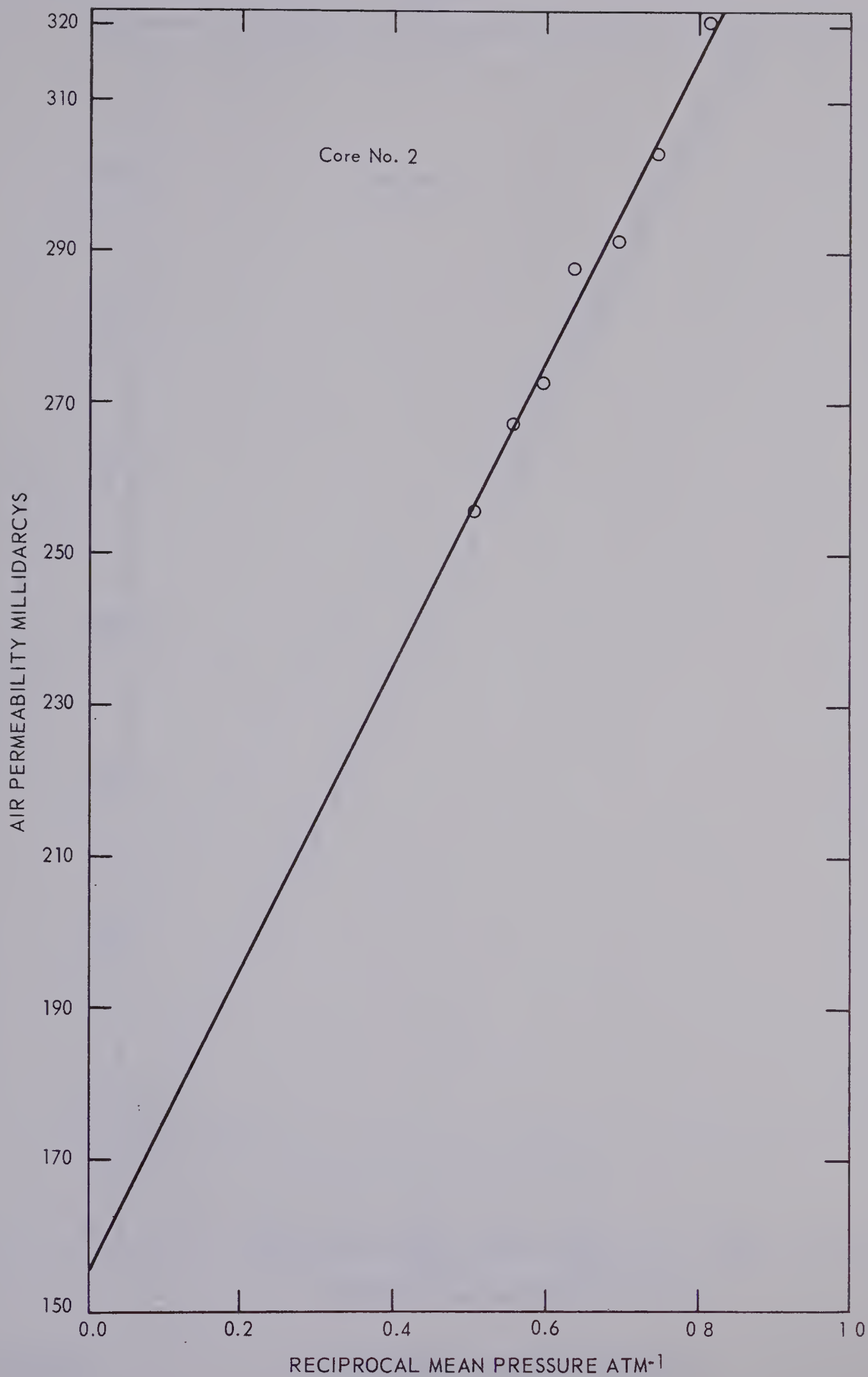


Figure I-2

KLINKENBERG CORRECTION PLOT

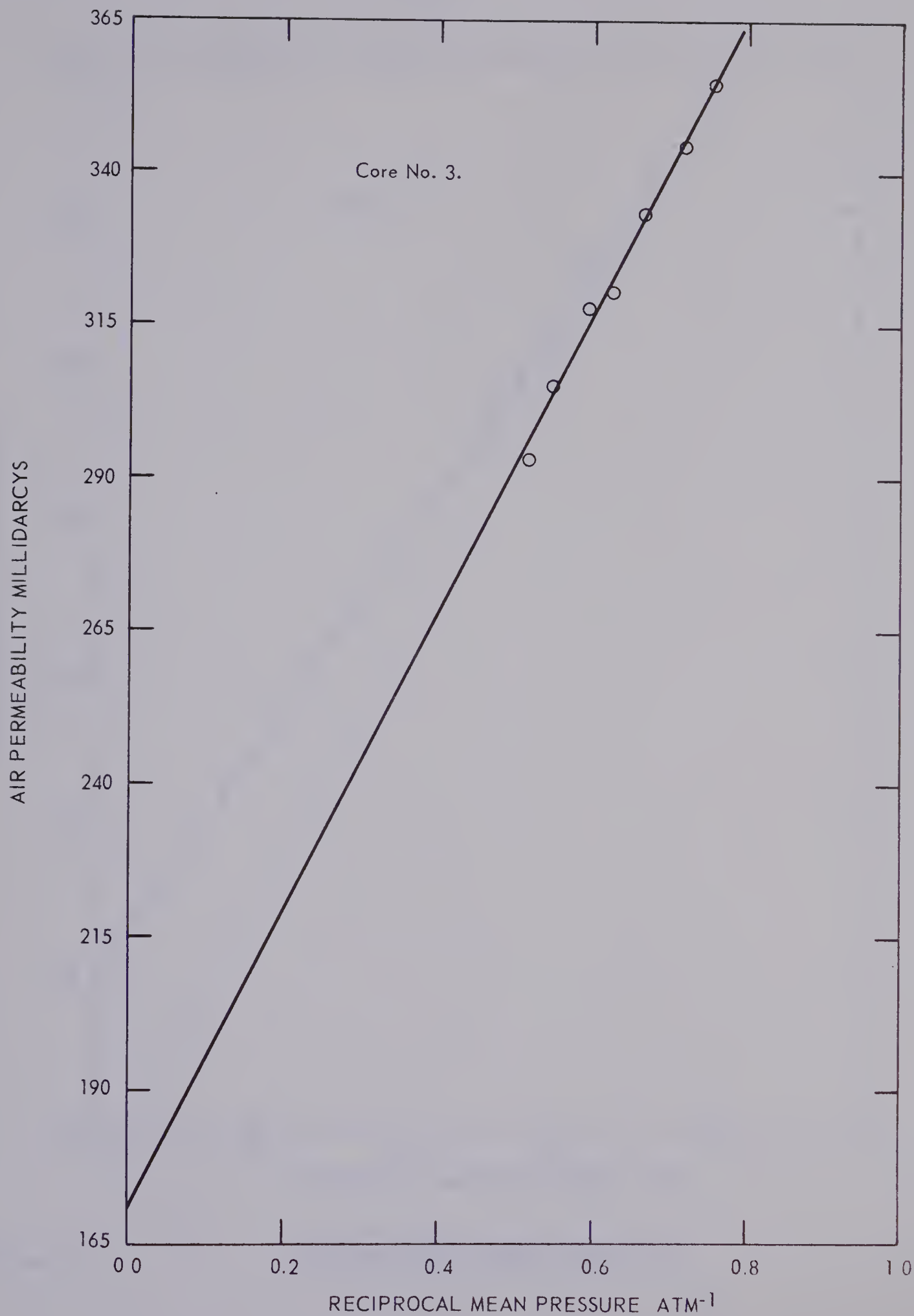


Figure I-3

KLINKENBERG CORRECTION PLOT

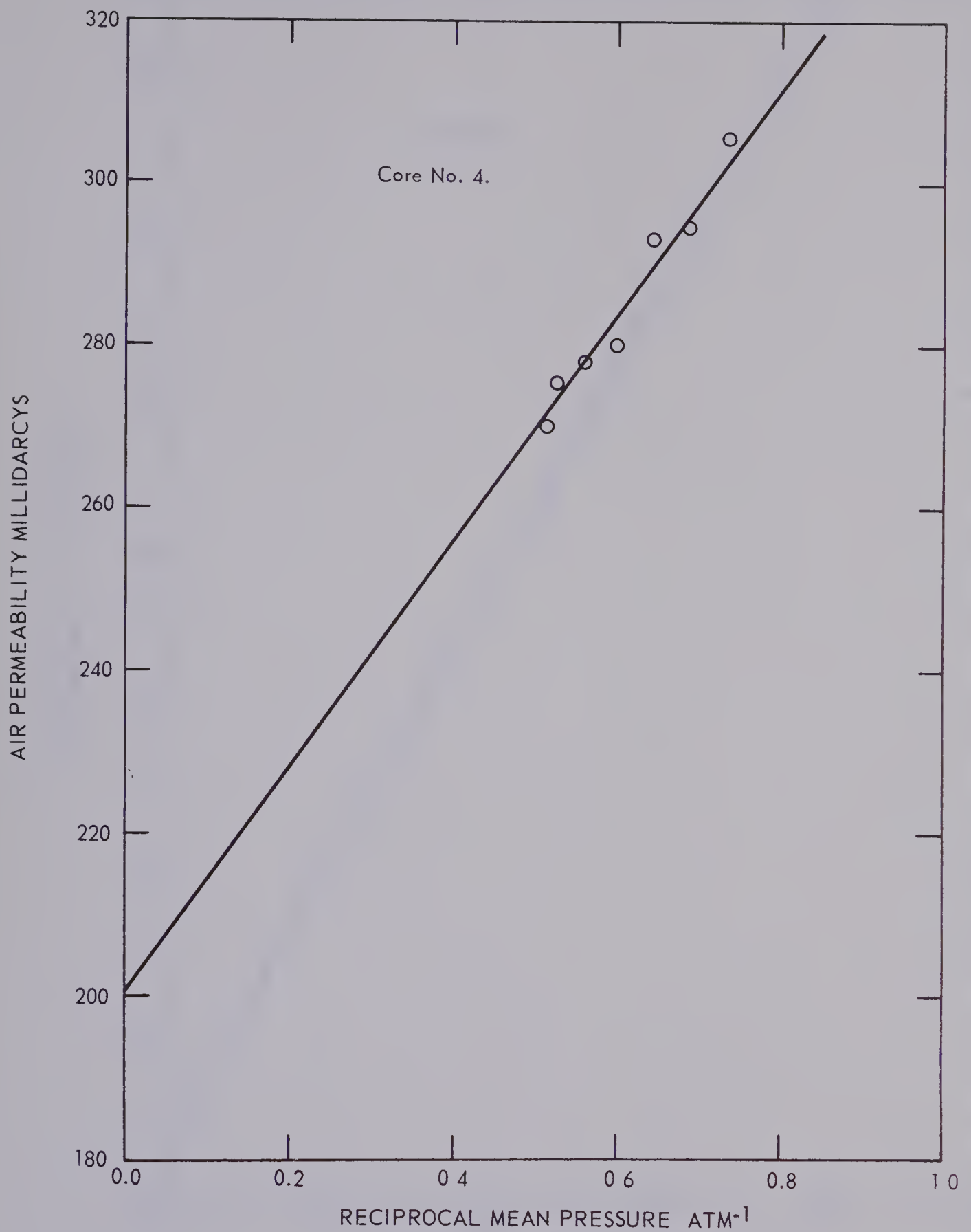


Figure I-4

KLINKENBERG CORRECTION PLOT

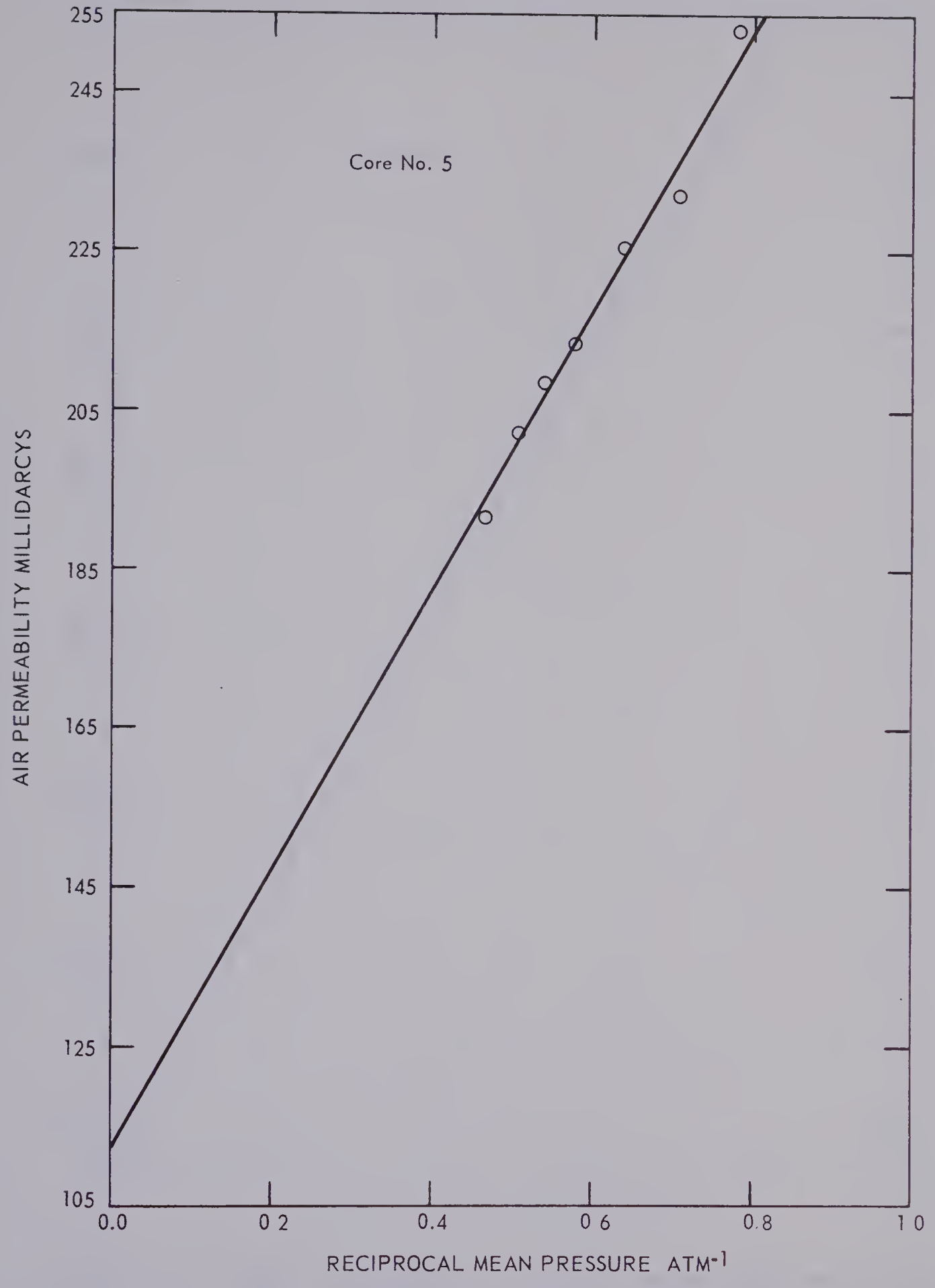


Figure I-5

KLINKENBERG CORRECTION PLOT

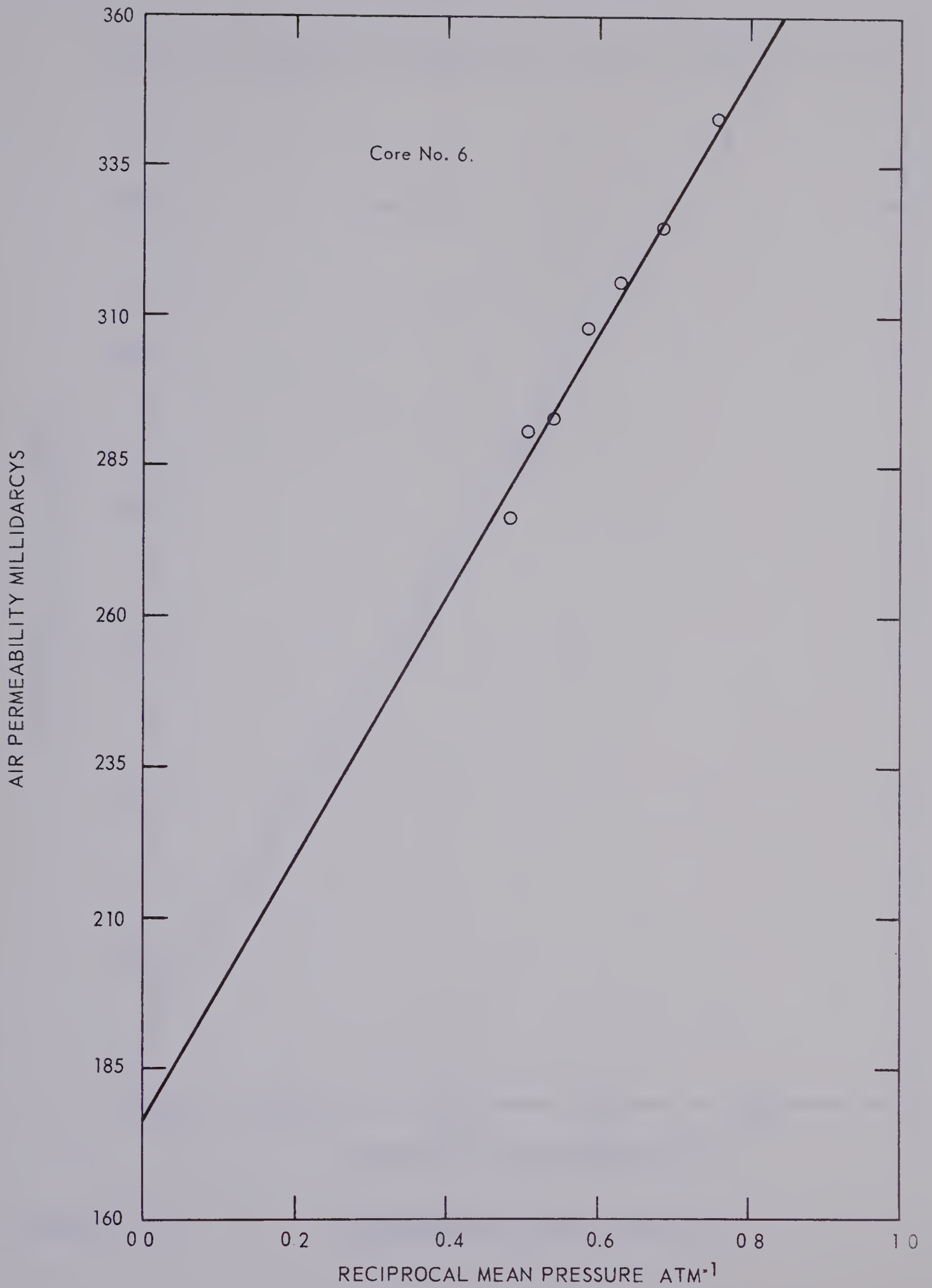


Figure I-6

KLINKENBERG CORRECTION PLOT

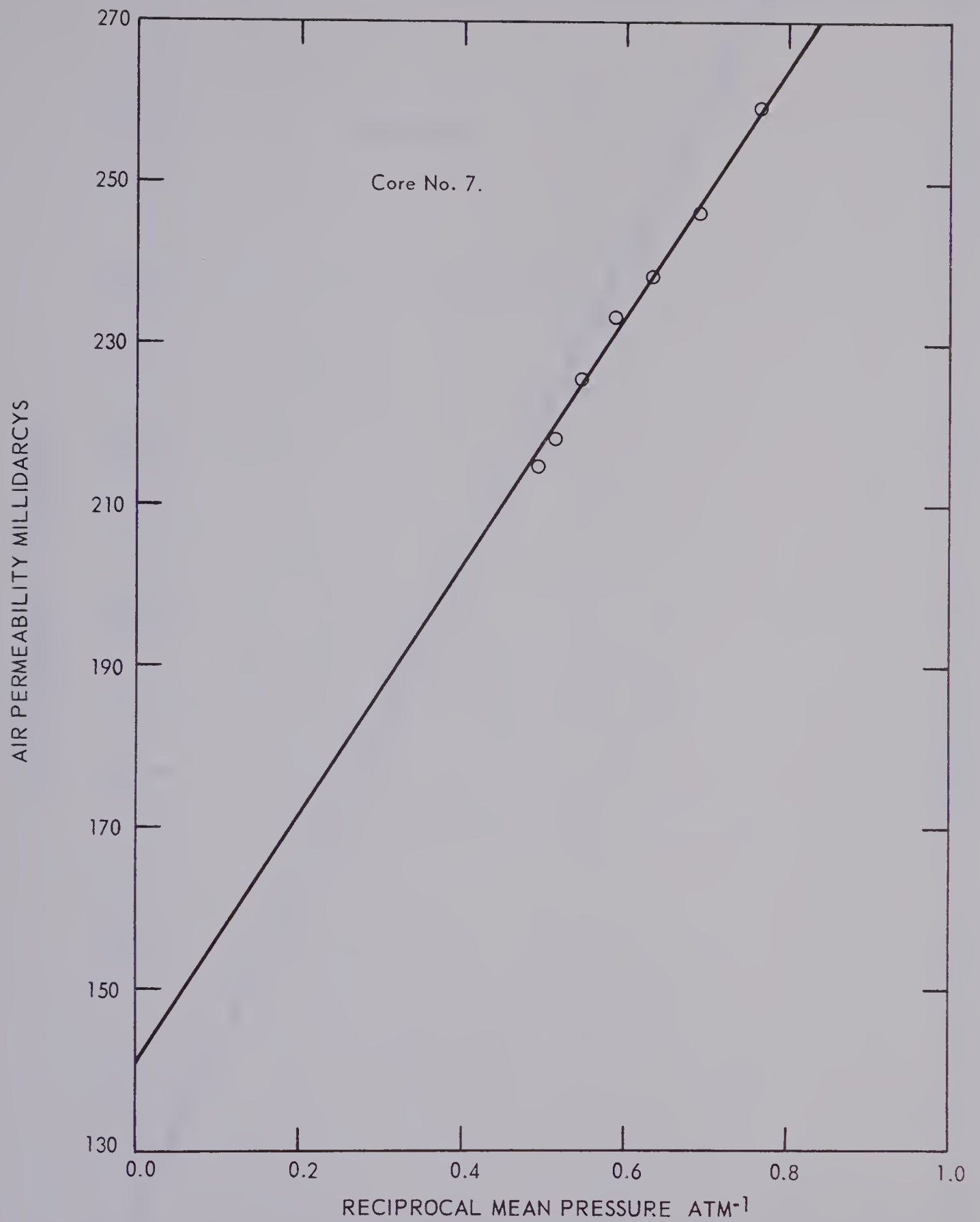


Figure I-7

KLINKENBERG CORRECTION PLOT

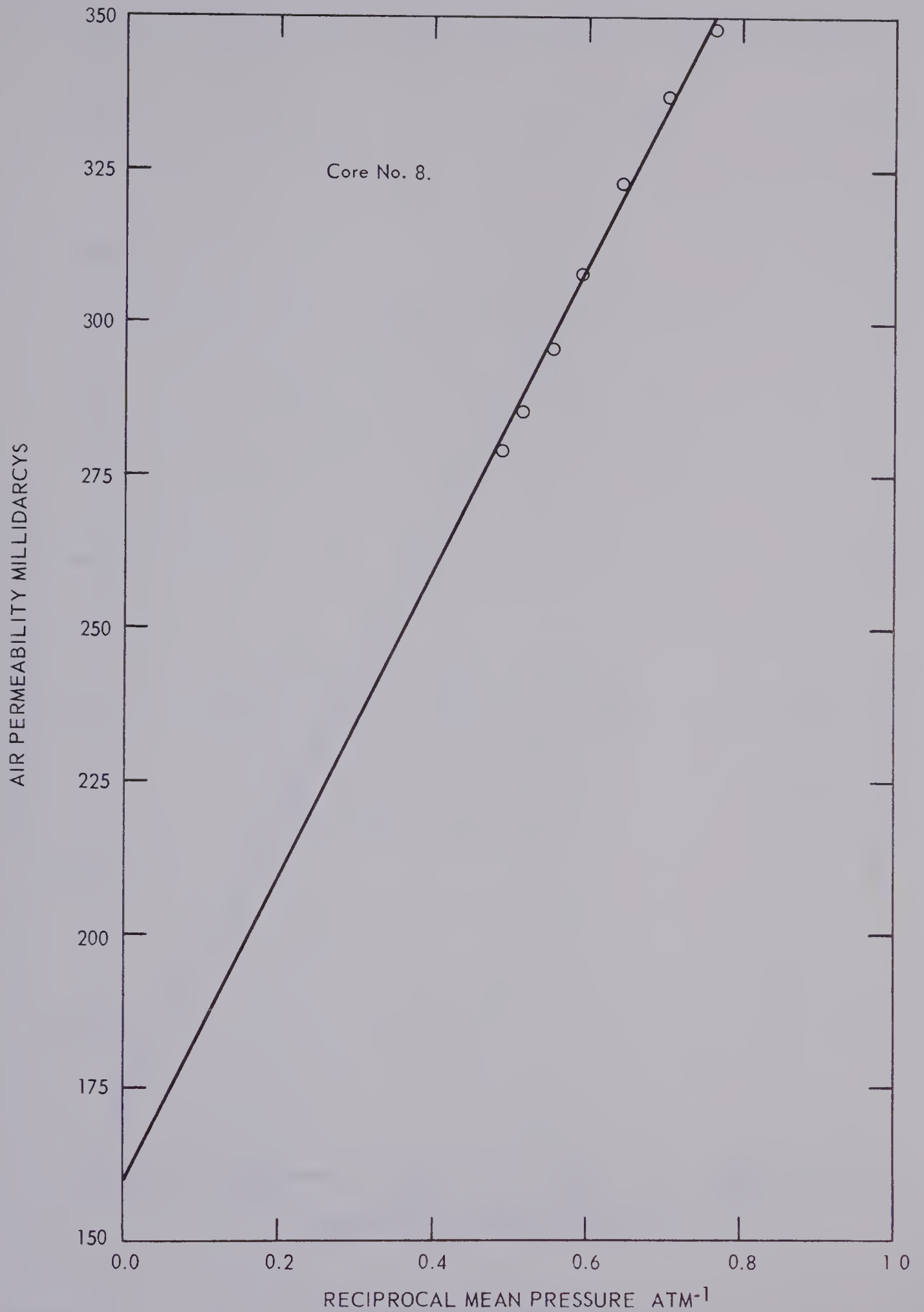


Figure I-8

KLINKENBERG CORRECTION PLOT

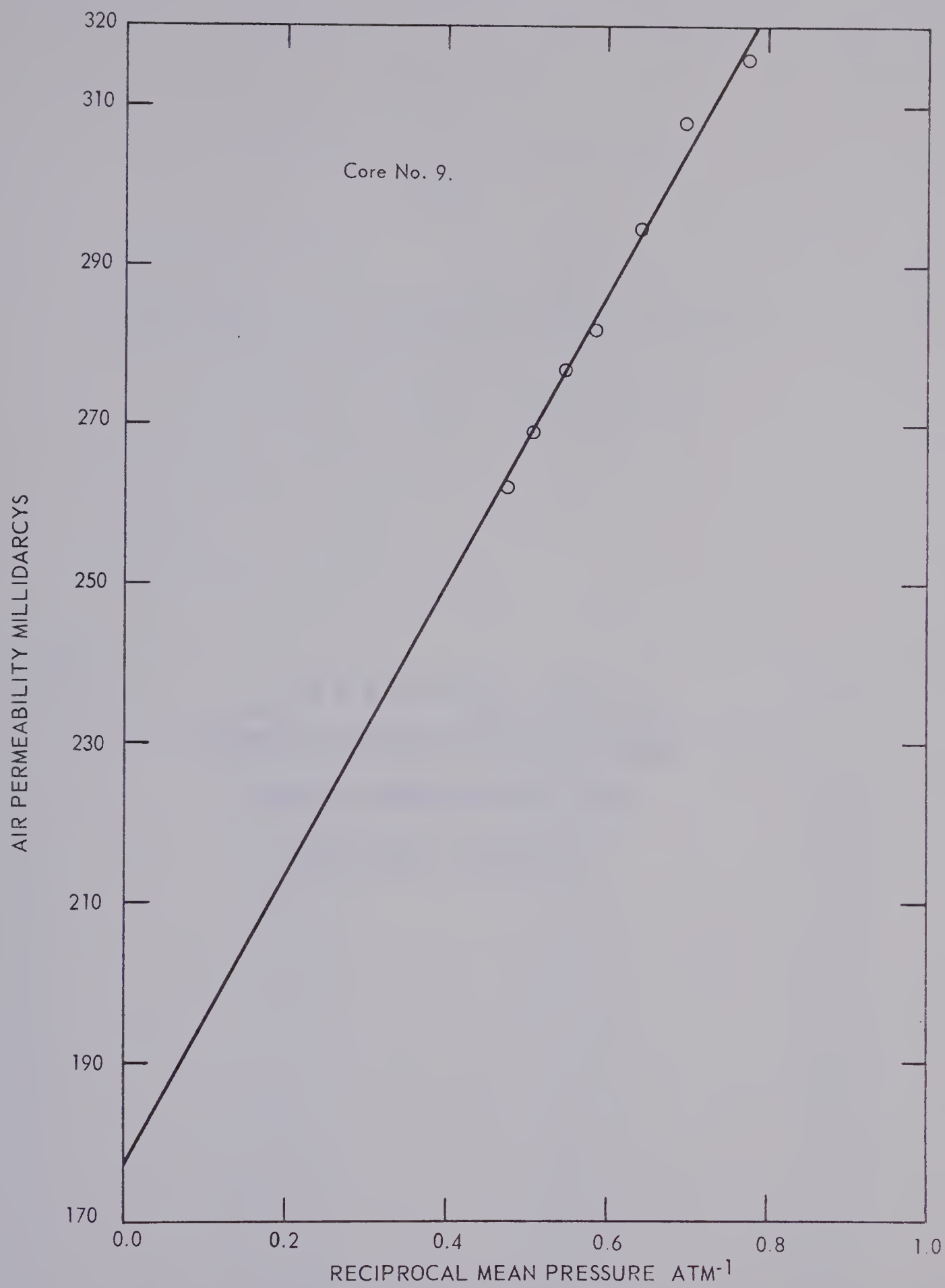


Figure I-9

KLINKENBERG CORRECTION PLOT

A P P E N D I X I I
MERCURY CAPILLARY PRESSURE DATA FROM
MANUALLY-OPERATED PURCELL CELL
FOR CORES 1 THROUGH 9

Table II-1
Mercury Capillary Pressure Data

Core 1

Barometric Pressure = 27.452 ins. Hg

Mercury pump scale reading when Hg is at mark in upper window of the cell

1. Without core in cell = 28.295 c c

2. With core in cell = 15.035 c c

Bulk Volume = 13.260 c c

Porosity = 0.320

Pore Volume = 4.243 c c

Cum.Vol.Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.29700	0.57660	0.06999	3.00776
0.88700	0.73435	0.20904	1.85431
0.17700	0.80187	0.27738	1.55521
1.44299	0.88810	0.34007	1.26787
1.57699	0.91751	0.37165	1.18788
2.06399	1.95903	0.48642	0.26056
2.25699	3.93997	0.53190	0.06441
2.30699	4.96788	0.54369	0.04051
2.34699	5.92091	0.55312	0.02852
2.44699	10.78817	0.57668	0.00859
2.54299	18.27626	0.59931	0.00299
2.60099	25.56013	0.61298	0.00153
2.67399	37.33686	0.63018	0.00071
2.73399	54.21908	0.64432	0.00034
2.79099	71.03324	0.65775	0.00019

Table II-2

Mercury Capillary Pressure Data

Core 2

Barometric Pressure = 27.452 ins. Hg

Mercury pump scale reading when Hg is at mark in upper window of the cell

1. Without core in cell = 27.285 c c

2. With core in cell = 14.035 c c

Bulk Volume = 13.250 c c

Porosity = 0.293

Pore Volume = 3.882 c c

Cum. Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.51800	0.62005	0.13342	2.60100
1.08800	0.76209	0.28024	1.72177
1.35800	0.85066	0.34979	1.38190
1.81799	1.32595	0.46828	0.56877
2.08800	2.89164	0.53783	0.11959
2.18799	4.18504	0.56359	0.05709
2.32800	7.62275	0.59965	0.01720
2.46799	17.25516	0.63571	0.00335
2.55599	29.50839	0.65838	0.00114
2.60599	39.71943	0.67126	0.00063
2.64599	51.29193	0.68156	0.00038
2.68599	64.22591	0.69186	0.00024
2.71599	75.79841	0.69959	0.00017
2.73899	83.96722	0.70551	0.00014
2.75899	89.41310	0.71067	0.00012

Table II-3

Mercury Capillary Pressure Data

Core 3

Barometric Pressure = 27.790 ins. Hg

Mercury pump scale reading when Hg is at mark in upper window of the cell

1. Without core in cell = 31.193 c c

2. With core in cell = 17.496 c c

Bulk Volume = 13.697 c c

Porosity = 0.255

Pore Volume = 3.492 c c

Cum. Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.20600	0.59458	0.05897	2.82860
0.81400	0.72827	0.23305	1.88542
1.23400	0.85294	0.35330	1.37455
1.41400	0.92881	0.40484	1.15916
1.77399	1.67761	0.50791	0.35531
1.95399	2.97442	0.55944	0.11305
2.04400	4.16230	0.58521	0.05772
2.16400	7.70212	0.61957	0.01685
2.26899	14.74773	0.64963	0.00459
2.38899	30.74502	0.68399	0.00105
2.44199	43.33862	0.69916	0.00053
2.49399	58.58709	0.71405	0.00029
2.49399	58.58709	0.71405	0.00029
2.53799	72.61025	0.72665	0.00018
2.55799	84.31889	0.73237	0.00014
2.58799	93.50882	0.74096	0.00011

Table II-4
Mercury Capillary Pressure Data
Core 4

Barometric Pressure = 27.790 ins. Hg

Mercury pump scale reading when Hg is at mark in upper window of the cell

1. Without core in cell = 31.250 c c

2. With core in cell = 17.920 c c

Bulk Volume = 13.330 c c

Porosity = 0.241

Pore Volume = 3.212 c c

Cum.Vol.Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.17500	0.52606	0.05447	3.61338
0.47900	0.62466	0.14910	2.56274
1.24900	0.82185	0.38879	1.48049
1.51900	0.92881	0.47283	1.15916
1.90899	1.57550	0.59423	0.40286
2.13100	2.86890	0.66334	0.12149
2.23100	4.33248	0.69446	0.05327
2.34100	7.34133	0.72870	0.01855
2.50699	16.82398	0.78038	0.00353
2.62699	31.57551	0.81773	0.00100
2.68899	44.50948	0.83703	0.00050
2.73599	57.51153	0.85166	0.00030
2.77999	71.73889	0.86536	0.00019
2.81999	84.65926	0.87781	0.00013
2.85999	95.57143	0.89026	0.00010

Table II-5

Mercury Capillary Pressure Data

Core 5

Barometric Pressure = 27.750 ins. Hg

Mercury pump scale reading when Hg is at mark in upper window of the cell

1. Without core in cell = 33.760 c c

2. With core in cell = 20.440 c c

Bulk Volume = 13.319 c c

Porosity = 0.205

Pore Volume = 2.730 c c

Cum.Vol.Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.12400	0.52640	0.04541	3.60879
0.35200	0.61998	0.12890	2.60156
0.47000	0.66677	0.17212	2.24924
0.70400	0.81383	0.25781	1.50982
1.05200	1.43121	0.38526	0.48819
1.28100	2.96967	0.46912	0.11339
1.35199	4.20861	0.49512	0.05645
1.47099	7.40807	0.53870	0.01822
1.60499	17.40127	0.58778	0.00330
1.65199	28.02073	0.60499	0.00127
1.74199	44.49454	0.63795	0.00050
1.77999	58.65382	0.65187	0.00029
1.81999	71.58781	0.66652	0.00019
1.84699	81.52654	0.67640	0.00015
1.87899	92.69060	0.68812	0.00011

Table II-6
Mercury Capillary Pressure Data
Core 6

Barometric Pressure = 27.620 ins. Hg

Mercury pump scale reading when Hg is at mark in
upper window of the cell

1. Without core in cell = 35.590 c c

2. With core in cell = 22.130 c c

Bulk Volume = 13.460 c c

Porosity = 0.225

Pore Volume = 3.028 c c

Cum.Vol.Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.08800	0.56383	0.02905	3.14552
0.46800	0.63435	0.15453	2.48502
0.81800	0.75768	0.27010	1.74188
1.13800	0.87967	0.37576	1.29226
1.27799	0.92312	0.42199	1.17348
1.64799	1.65151	0.54416	0.36663
1.83799	3.03340	0.60690	0.10867
1.90799	4.22469	0.63001	0.05602
2.00799	6.91359	0.66303	0.02092
2.17799	19.09876	0.71916	0.00274
2.24799	30.87548	0.74228	0.00104
2.28799	44.49019	0.75548	0.00050
2.33099	58.78563	0.76968	0.00028
2.37499	72.38671	0.78421	0.00019
2.40999	90.91633	0.79577	0.00012

Table II-7

Mercury Capillary Pressure Data

Core 7

Barometric Pressure = 27.830 ins. Hg

Mercury pump scale reading when Hg is at mark in upper window of the cell

1. Without core in cell = 33.440 c c

2. With core in cell = 20.280 c c

Bulk Volume = 13.159 c c

Porosity = 0.205

Pore Volume = 2.697 c c

Cum.Vol.Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.09600	0.57987	0.03558	2.97388
0.32600	0.62934	0.12083	2.52477
0.78600	0.81985	0.29134	1.48774
1.04600	0.92012	0.38772	1.18116
1.15600	0.93014	0.42849	1.15583
1.58599	1.81510	0.58788	0.30352
1.73599	2.97235	0.64348	0.11318
1.80599	4.26574	0.66943	0.05495
1.92599	7.73750	0.71391	0.01670
2.07599	17.94853	0.76951	0.00310
2.16599	32.78856	0.80287	0.00093
2.19599	46.40327	0.81399	0.00046
2.24599	62.87706	0.83252	0.00025
2.29399	79.75930	0.85032	0.00012
2.32799	92.28483	0.86292	0.00011

Table II-8

Mercury Capillary Pressure Data

Core 8

Barometric Pressure = 27.560 ins. Hg

Mercury pump scale reading when Hg is at mark in upper window of the cell

1. Without core in cell = 35.890 c c

2. With core in cell = 22.690 c c

Bulk Volume = 13.200 c c

Porosity = 0.263

Pore Volume = 3.471 c c

Cum.Vol.Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.09700	0.56885	0.02794	3.09032
0.26700	0.59024	0.07690	2.87039
0.94700	0.74899	0.27278	1.78254
1.26699	0.89939	0.36496	1.23622
1.39700	0.92112	0.40240	1.17859
1.74699	1.46230	0.50322	0.46765
1.98699	2.96469	0.57235	0.11377
2.06199	4.05522	0.59396	0.06080
2.16799	6.77580	0.62449	0.02177
2.36099	20.79859	0.68008	0.00231
2.43699	34.41330	0.70198	0.00084
2.49099	47.75572	0.71753	0.00043
2.52799	62.86804	0.72819	0.00025
2.56399	79.20569	0.73856	0.00015
2.60299	90.50589	0.74979	0.00012

Table II-9

Mercury Capillary Pressure Data

Core 9

Barometric Pressure = 27.630 ins. Hg

Mercury pump scale reading when Hg is at mark in upper window of the cell

1. Without core in cell = 32.350 c c

2. With core in cell = 19.050 c c

Bulk Volume = 13.300 c c

Porosity = 0.214

Pore Volume = 2.846 c c

Cum. Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled with Hg	1/Pres. ² atm ⁻²
0.08800	0.53041	0.03091	3.55442
0.23800	0.58021	0.08362	2.97046
0.62800	0.64070	0.22064	2.43601
0.99800	0.70955	0.35064	1.98620
1.26800	0.92346	0.44550	1.17263
1.68799	1.77438	0.59307	0.31761
1.87799	3.44218	0.65982	0.08439
2.00799	6.09705	0.70550	0.02690
2.10299	9.92959	0.73887	0.01014
2.21099	19.98405	0.77682	0.00250
2.29099	34.55178	0.80493	0.00083
2.35199	51.63824	0.82636	0.00037
2.40799	70.63078	0.84603	0.00020
2.43799	80.02491	0.85658	0.00015
2.46799	90.37209	0.86712	0.00012

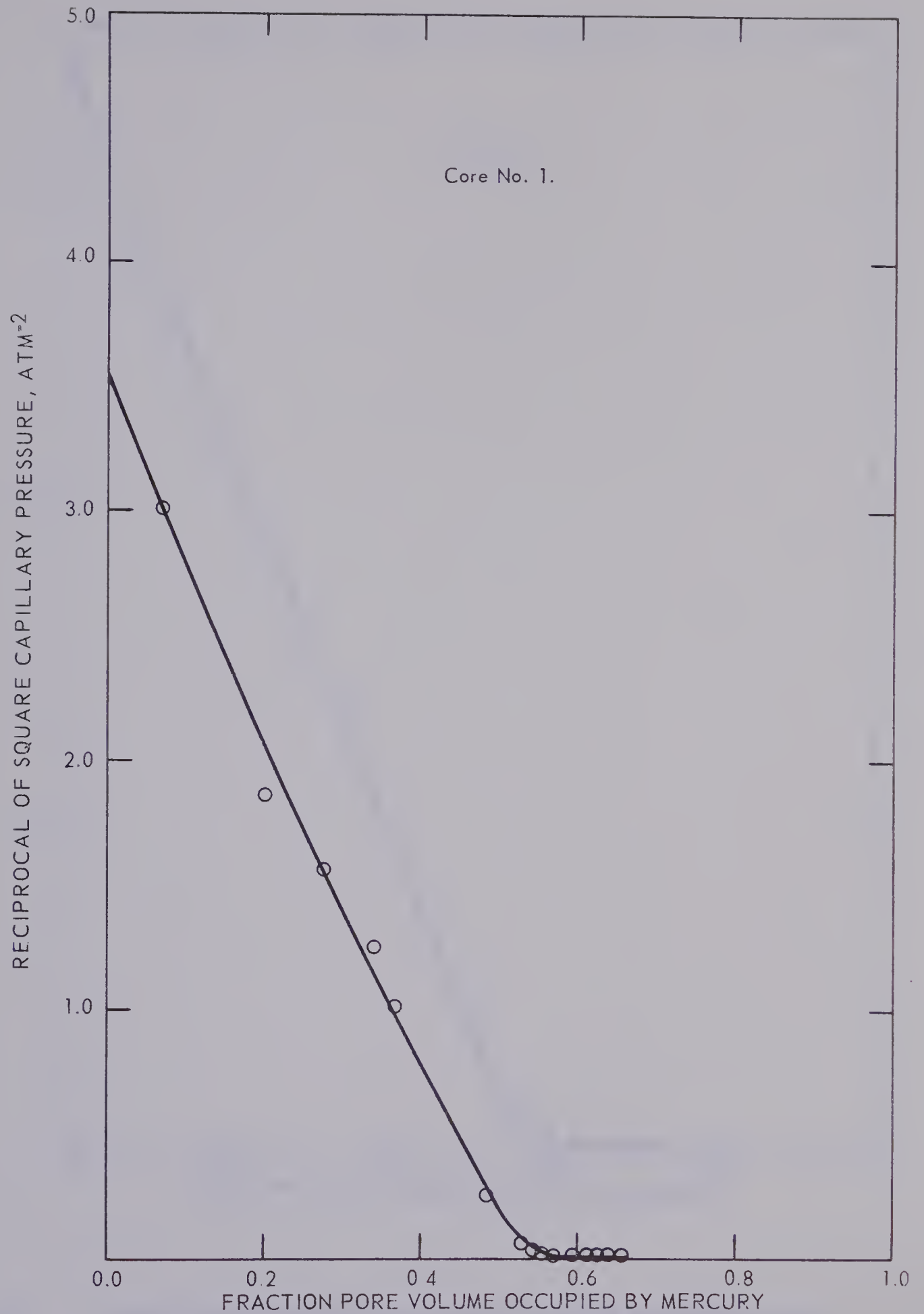


Figure II-1 FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE

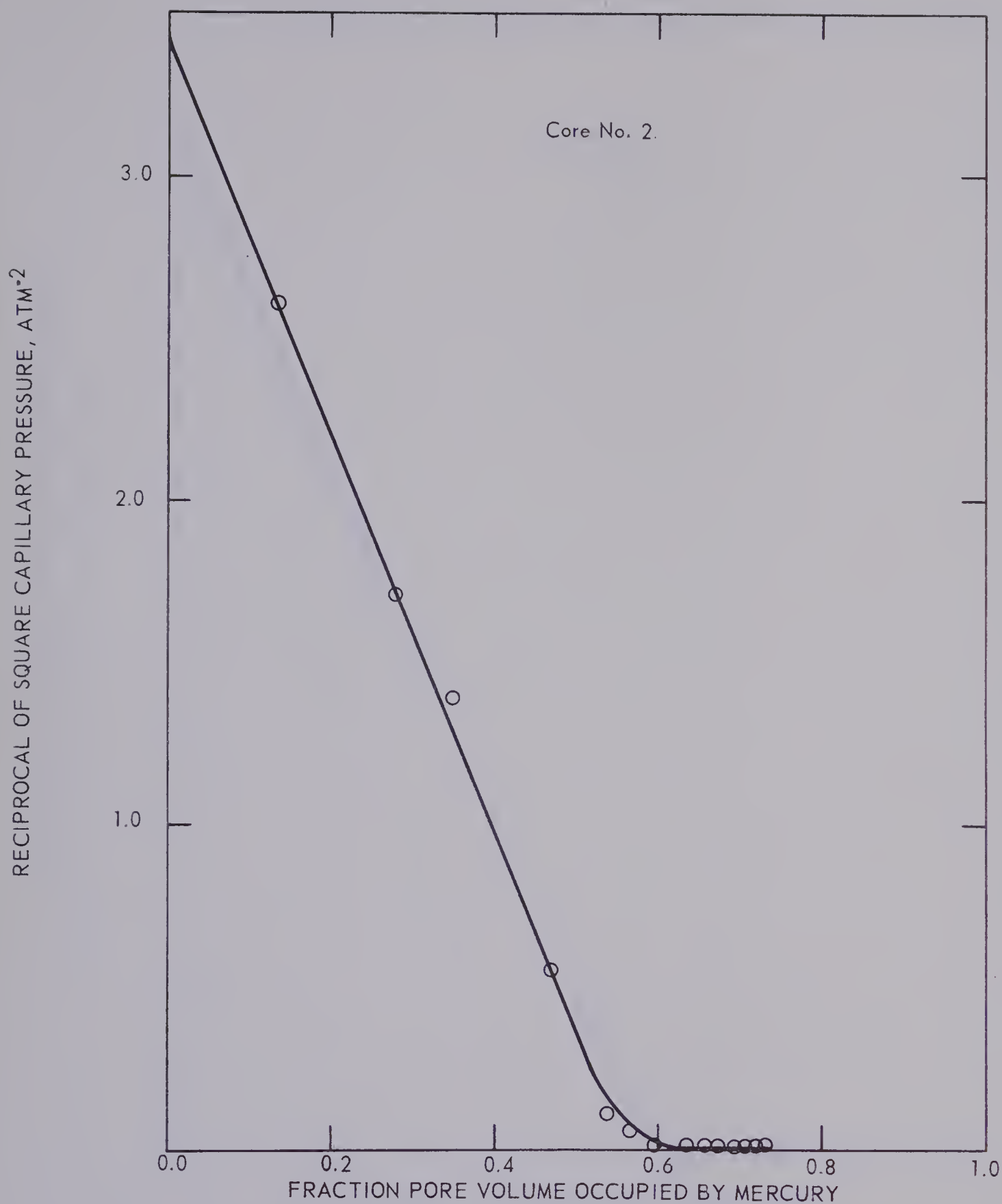


Figure II-2.

FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF
SQUARE CAPILLARY PRESSURE

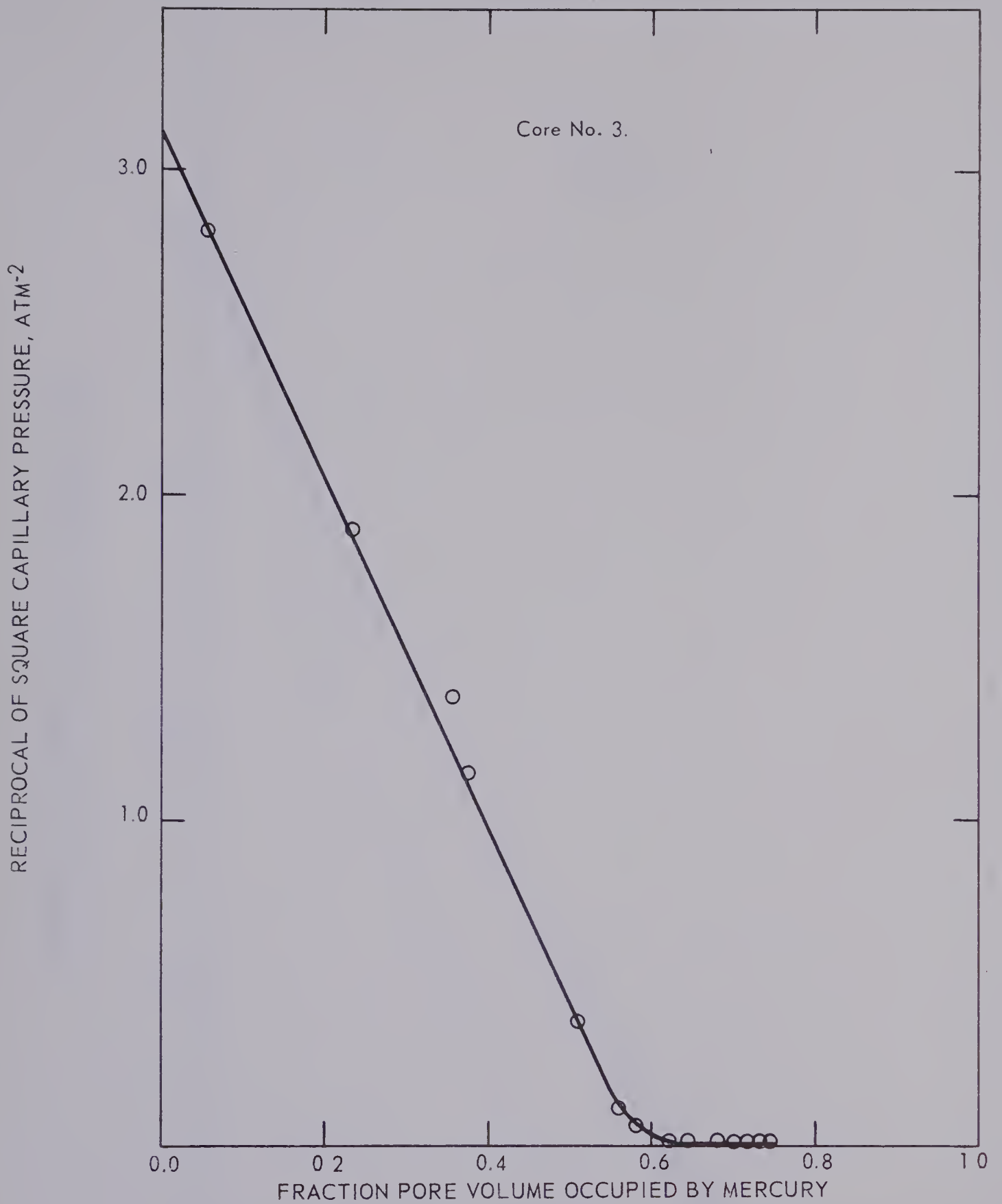


Figure II-3. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE

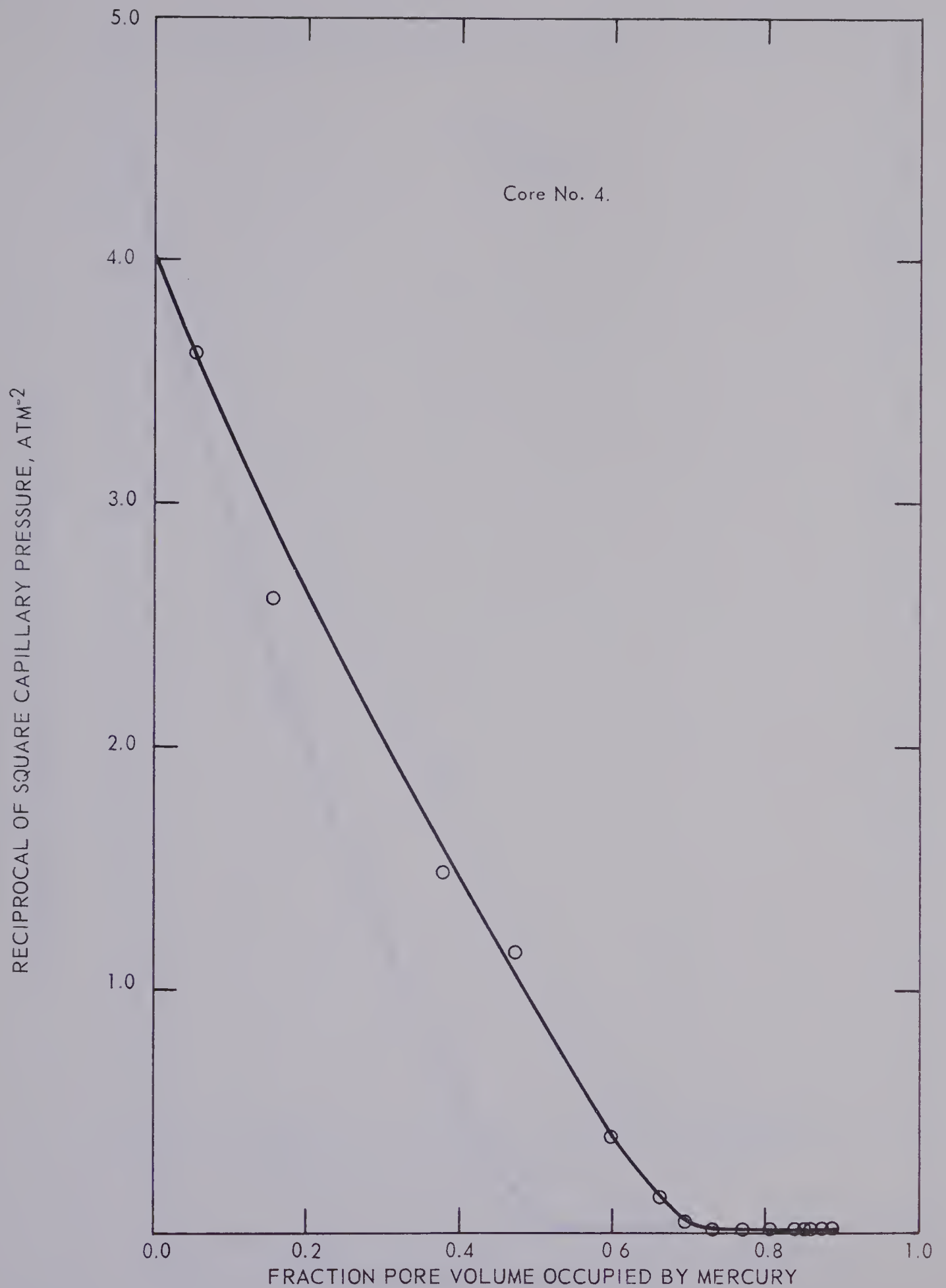


Figure II-4. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE.

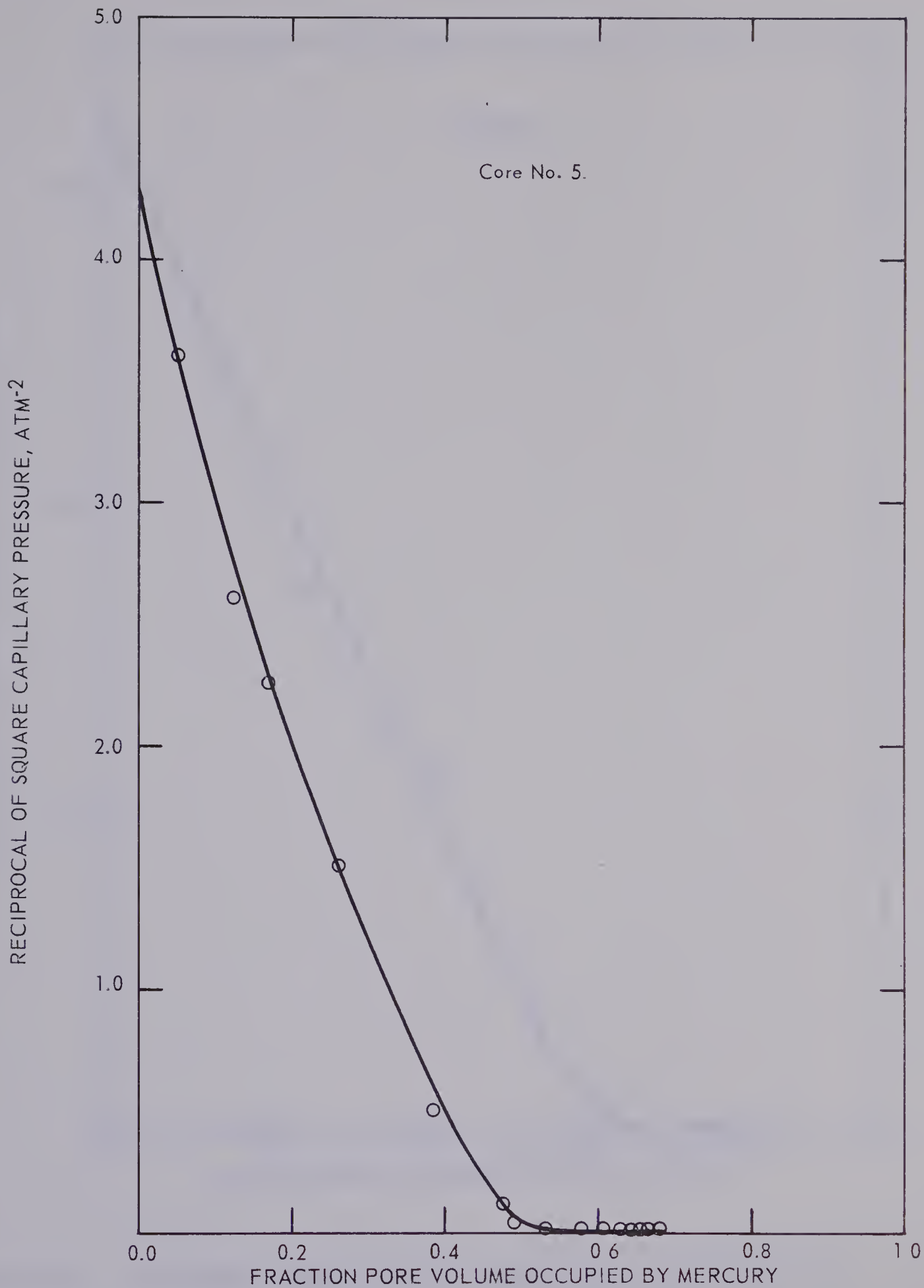


Figure II-5. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE

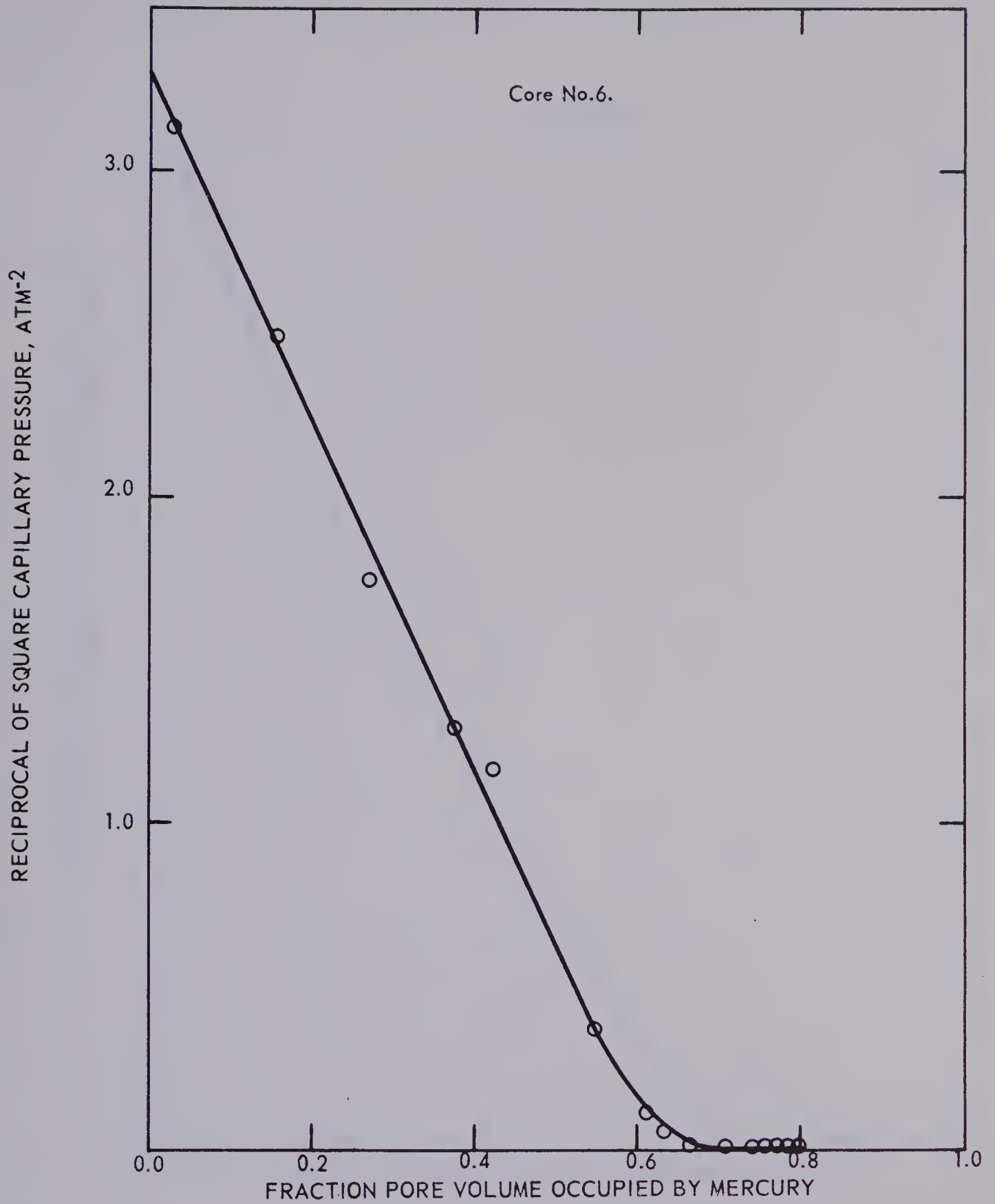


Figure II-6. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE.

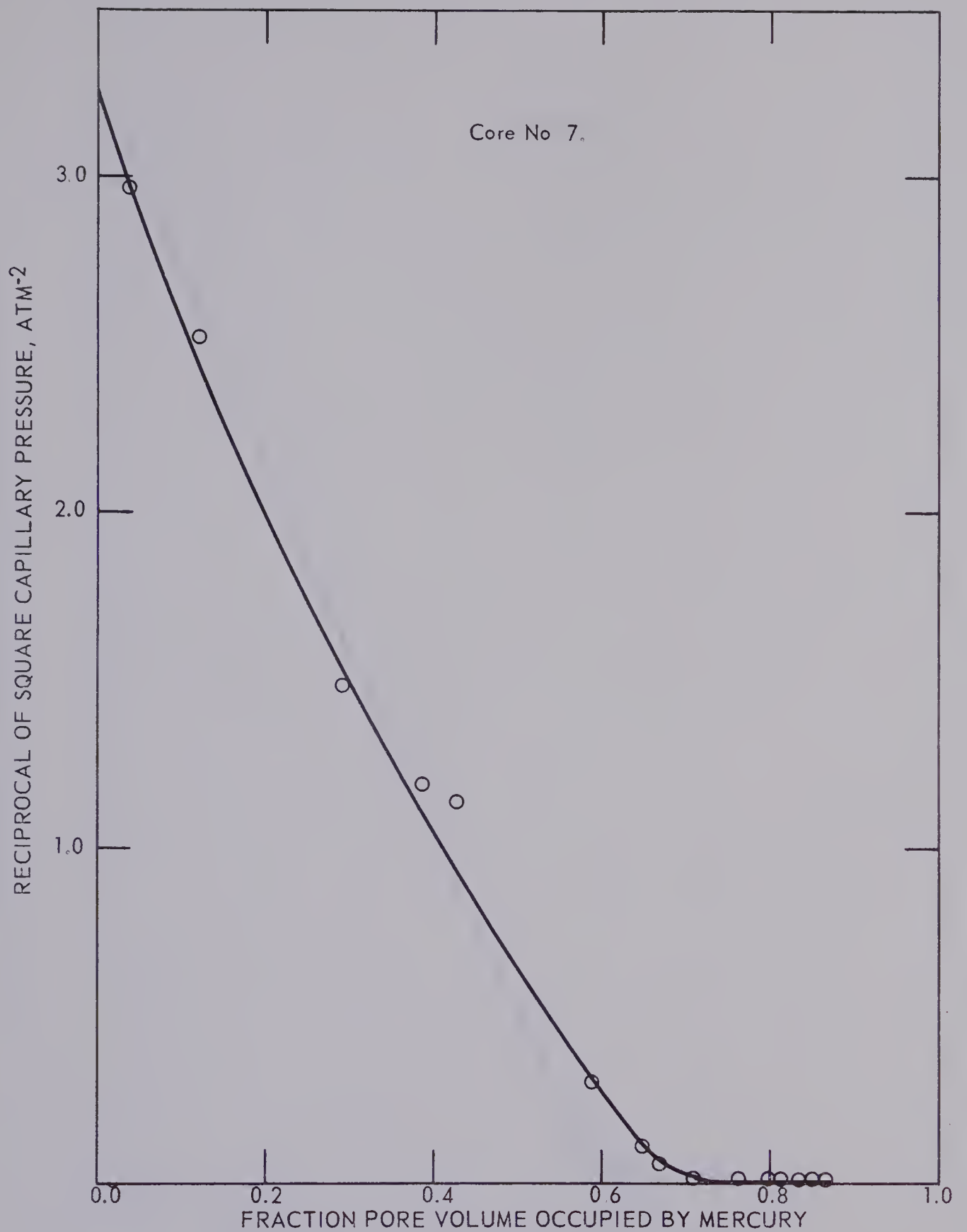


Figure II-7. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE.

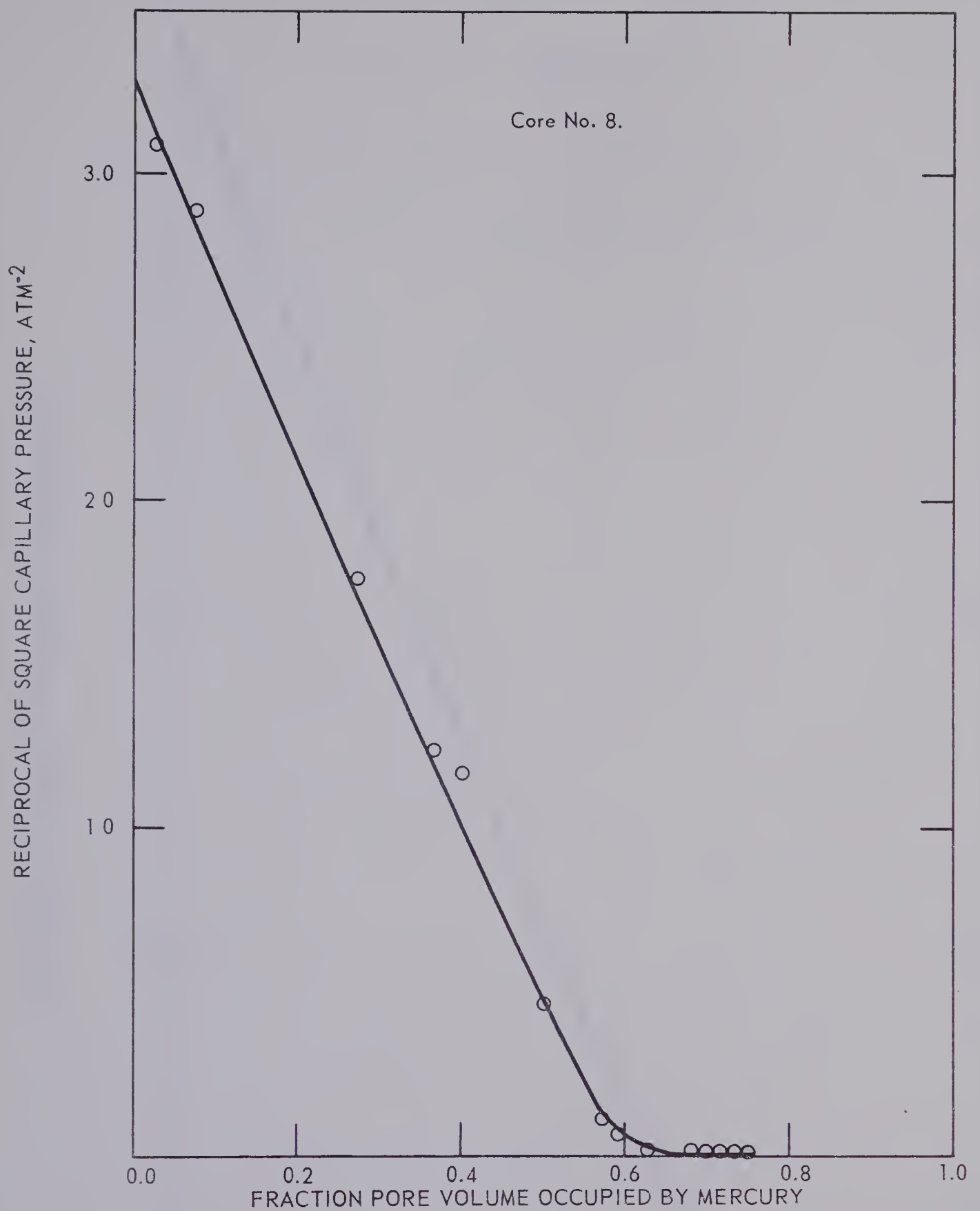


Figure II-8. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE.

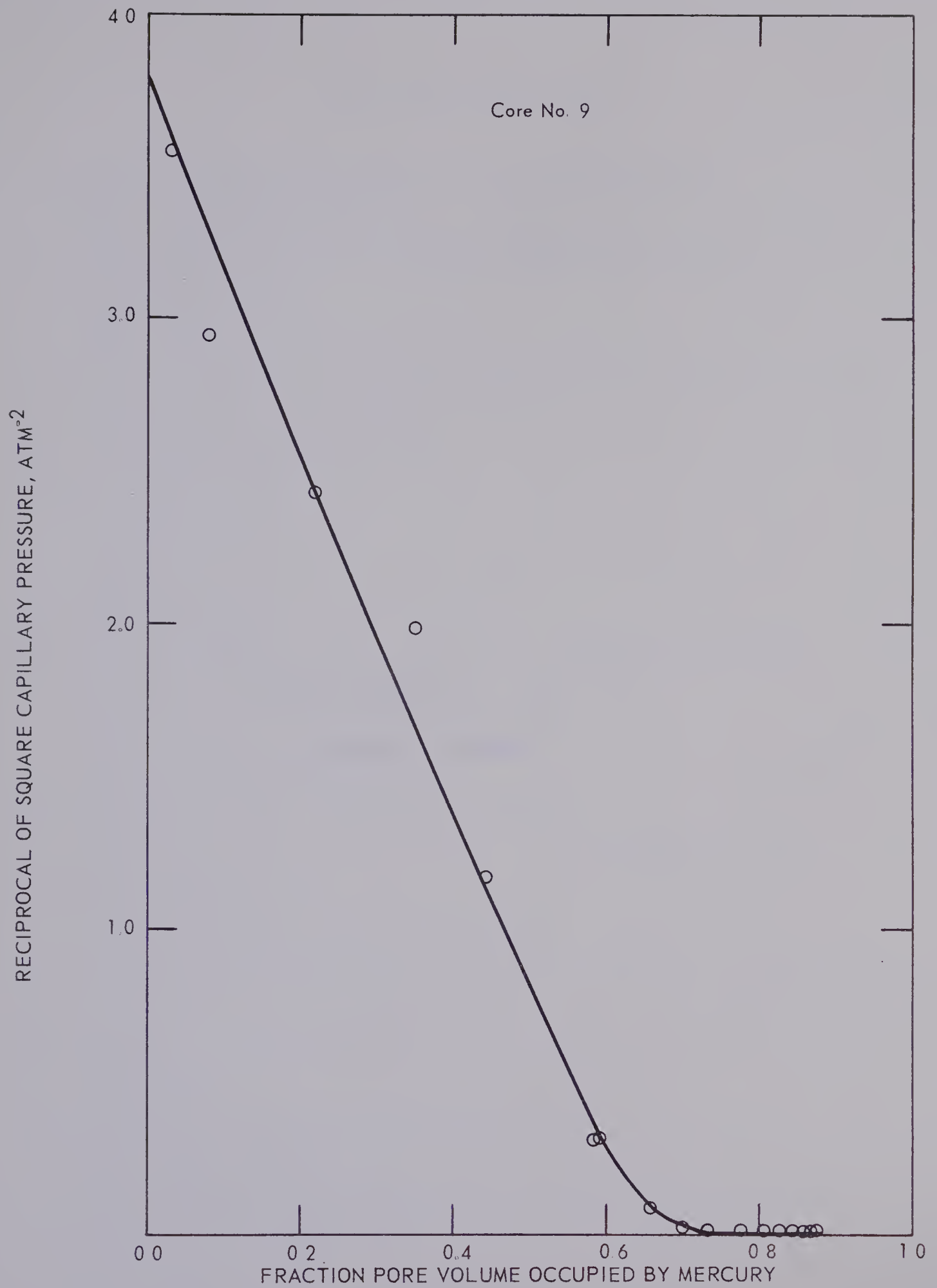


Figure II-9. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE.

A P P E N D I X I I I

LISTING OF PROGRAMS

C

Main Line Program PlCO4

C

```
DEFINE FILE 87(20,20,U,I87),88(30,30,U,I88)
EXTERNAL CHAUD,MAHMD
DIMENSION ARRAY(4),POR(5),PRES(5),VOL(5),Z(1),PV(1)
EQUIVALENCE (ARRAY(1),AVVLB),(ARRAY(2),AVPRA)
1,(ARRAY(3),PPV)
1,(ARRAY(4),RPS)
CALL DOUT1(4,15,1)
CALL DIGIN(069,0,4,IVLUE)
GO TO (100,101,102,103,104,105,106,107,108,109),IVLUE
107 CALL QUEUE(MAHMD,32767,0)
GO TO 450
106 CALL QUEUE(CHAUD,32767,0)
GO TO 450
108 READ(87'1)ILOC
ILOC=ILOC+1
WRITE(87'1)ILOC
GO TO 450
109 READ(87'2)YZ
WRITE(6,666)YZ
666 FORMAT('0',10X,'AREA UNDER THE CURVE =',F10.5,2X
1,'ATMOSP **(-2)')
READ(87'1)ILOC
ILOC=ILOC+1
READ(87'ILOC)POR(ILOC)
WRITE(6,656)POR(ILOC)
656 FORMAT('0',10X,'POROSITY=',F10.5)
WRITE(6,952)
952 FORMAT('0',10X,'CALCU. PERM. = 0.66*POROSITY*AREA
1 UNDER CURVE*100
20.0',2X,'MD')
PERM=0.66*POR(ILOC)*YZ*10000.0
WRITE(6,657)PERM
657 FORMAT('0',10X,'CALCU. PERM.=',F10.5,2X,'MILLIDARCYS')
GO TO 450
105 ILOC=1
WRITE(87'1)ILOC
GO TO 450
101 DO 201 I=1,4
CALL AIP (11000,IPRES,120)
1 CALL AIP (00000,ITEST)
GO TO(1,2),ITEST
2 CALL AIP (11000,IVOL,47)
3 CALL AIP (00000,ITEST)
GO TO (3,4),ITEST
4 CONTINUE
PRES(I)=(50.0*IPRES)/26214.0
VOL(I)=(46.1*IVOL)/32767.0
201 CONTINUE
AVPRA=(PRES(1)+PRES(2)+PRES(3)+PRES(4))/(4.0*14.69)
```


P1C04

C

```
      AVVL=(VOL(1)+VOL(2)+VOL(3)+VOL(4))/4.0
      READ(88'2)AVVL1
      AVVLB=AVVL-AVVL1
      READ(87'1)ILOC
      WRITE(88'ILOC)AVVLB,AVPRA
      ILOC=ILOC+1
      WRITE(87'1)ILOC
      CONTINUE
      GO TO 450
102 DO 901 I=1,4
      CALL AIP (11000,IPRES,121)
11  CALL AIP (00000,ITEST)
      GO TO(11,22),ITEST
      22 CALL AIP (11000,IVOL,47)
      33 CALL AIP (00000,ITEST)
      GO TO (33,44),ITEST
      44 CONTINUE
      PRES(I)=(100.0*IPRES)/26214.0
      VOL(I)=(46.1*IVOL)/32767.0
901 CONTINUE
      AVPRA=(PRES(1)+PRES(2)+PRES(3)+PRES(4))/(4.0*14.69)
      AVVL=(VOL(1)+VOL(2)+VOL(3)+VOL(4))/4.0
      READ(88'2)AVVL1
      AVVLB=AVVL-AVVL1
      READ(87'1)ILOC
      WRITE(88'ILOC)AVVLB,AVPRA
      ILOC=ILOC+1
      WRITE(87'1)ILOC
      CONTINUE
      GO TO 450
103 DO 701 I=1,4
      CALL AIP (11000,IPRES,122)
111 CALL AIP (00000,ITEST)
      GO TO(111,222),ITEST
      222 CALL AIP (11000,IVOL,47)
      333 CALL AIP (00000,ITEST)
      GO TO (333,444),ITEST
      444 CONTINUE
      PRES(I)=(1500.0*IPRES)/26214.0
      VOL(I)=(46.1*IVOL)/32767.0
701 CONTINUE
      AVPRA=(PRES(1)+PRES(2)+PRES(3)+PRES(4))/(4.0*14.69)
      AVVL=(VOL(1)+VOL(2)+VOL(3)+VOL(4))/4.0
      READ(88'2)AVVL1
      AVVLB=AVVL-AVVL1
      READ(87'1)ILOC
      WRITE(88'ILOC)AVVLB,AVPRA
      ILOC=ILOC+1
      WRITE(87'1)ILOC
      GO TO 450
```


P1C04

C

```
100 DO 86 I=1,4
    CALL AIP (11000,IVOL,47)
83 CALL AIP (00000,ITEST)
    GO TO(83,84),ITEST
84 CONTINUE
    VOL(I)=(46.1*IVOL)/32767.0
86 CONTINUE
    AVVL1=(VOL(1)+VOL(2)+VOL(3)+VOL(4))/4.0
    AVPRA=0.000
    READ(87'1)ILOC
    WRITE(88'ILOC)AVVL1,AVPRA
    ILOC=ILOC+1
    WRITE(87'1)ILOC
    GO TO 450
104 READ(88'2)X
    READ(88'1)Y
    Z(1)=Y-X
    WRITE(6,307)Z(1)
307 FORMAT('1'////////,11X,'BULK VOLUME=',F10.5,2X,'C.CS')
    READ(87'1)ILOC
    ILOC=ILOC+2
    READ(87'ILOC)POR(ILOC)
    WRITE(6,308)POR(ILOC)
308 FORMAT('0',10X,'POROSITY=',F10.5)
    PV(1)=Z(1)*POR(ILOC)
    WRITE(6,309)PV(1)
309 FORMAT('0',10X,'PORE VOLUME=',F10.5,2X,'C.CS')
    ILOC=2
    DO 603 I=1,18
        ILOC=ILOC+1
        READ(88'ILOC)ARRAY
        PPV=AVVLB/PV(1)
        RPS=1/(AVPRA**2)
603 WRITE(88'ILOC)ARRAY
        WRITE(6,564)
564 FORMAT('0',10X,'CUM VOL HG',1X,'PRESSURE',3X,'FRC
1 PORE',2X,'1/PRE
1S**2')
        WRITE(6,563)
563 FORMAT(' ',10X,'INJECTED',6X,'ATMOS',4X,'FILLED'4X
1,'ATM**(-2)')
        WRITE(6,562)
562 FORMAT(' ',12X,'C.CS',17X,'WITH HG')
        ILOC=2
        DO 605 I=1,15
            ILOC=ILOC+1
            READ(88'ILOC)ARRAY
605 WRITE(6,424)ARRAY
            CONTINUE
424 FORMAT(10X,6F10.5)
```


P1C04

C

```
450 CALL DOUT1(4,15,0)
    CALL VIAQ
    END
```


STAND

Subroutine STAND

C

C

```
EXTERNAL RNPLT
DIMENSION C(11),X1(100),Y1(100)
COMMON X(40),Y(40),N,ID,IS,IG,IL,IT,IB,IU,IR,IP,XMAX
1,XMIN,NCYCX,
1 YMAX,YMIN,NCYCY,NFILX,NFILY,NPTS,IND
DEFINE FILE 101(40,40,U,J1),102(40,40,U,J2),87(20,20,U
1,I87)
GO TO (100,200),IND
200 CALL VIAQ
100 IND=2
COMP=1.
M=15
N1=4
CALL CURVE (M,X,Y,N1,C,COMP)
NN=100
DO 2 I=1,NN
X1(I)=XMIN+(I-1)*(XMAX-XMIN)/(NN-1)
Y1(I)=C(1)
DO 3 J=1,N1
Y1(I)=Y1(I)+C(J+1)*X1(I)**J
3 CONTINUE
IF(Y1(I)-YMIN)4,2,5
4 Y1(I)=YMIN
GO TO 2
5 IF(Y1(I)-YMAX)2,2,6
6 Y1(I)=YMAX
2 CONTINUE
WRITE(101'1')(X1(I),I=1,NN)
WRITE(102'1')(Y1(I),I=1,NN)
NFILX=101
NFILY=102
IR=2
N=20
NPTS=NN
IS=2
IU=IG+1
IP=-1
CALL CHAIN (RNPLT)
END
```


STAND

C

C

C*****

C*****

C

C SUBROUTINE CURVE (M,X,Y,N,C,COMP)

C

C PURPOSE

C TO FIT A GIVEN SET OF POINTS WITH THE BEST FIT

C POLYNOMIAL

C WHOSE ORDER WILL BE FROM TWO TO THAT SPECIFIED BY

C THE USER

C WITH A PRESENT MAXIMUM OF FOUR

C

C PARAMETERS

C M - NUMBER OF DATA POINTS TO BE FITTED

C X - VECTOR OF M INDEPENDENT VALUES

C Y - VECTOR OF M DEPENDENT VALUES

C N - ENTER THE MAXIMUM ORDER OF POLYNOMIAL YOU
C WANT TRIED

C TO A MAXIMUM OF TEN

C - RETURNS THE ORDER OF THE BEST FIT

C POLYNOMIAL BETWEEN

C TWO AND N.

C C - VECTOR OF DIMENSION N+1 WHICH RETURNS THE
C N+1

C COEFFICIENTS OF THE BEST FIT POLYNOMIAL,

C $Y=C_0+C_1*X+C_2*X^2+C_3*X^3+\dots$

C COMP - SET TO 1. - PRINTS OUT A COMPARISON OF THE
C GIVEN POINTS

C AND THE CORRESPONDING ONES ON THE

C POLYNOMIAL

C SET TO 0. - NO COMPARISON

C

C *** IMPORTANT NOTE

*** THE MATRIX A IN THE

C **DIMENSION

C STATEMENT OF THIS SUBROUTINE MUST BE DIMENSIONED
C TO M*N

C

C

C*****

C*****

C

C

SUBROUTINE CURVE(M,X,Y,N,C,COMP)

DIMENSION X(1),Y(1),C(1),A(140),AUX(20),Z(25)

DIMENSION CS(11),VAR(10)

VAR(1)=1.E25

N1=N+1

STAND

C

```
DO 8 IORD=2,N1
DO 3 JORD=1,IORD
  ISTAR =(JORD-1)*M
  DO 3 IPTS=1,M
    IF(JORD-1)2,1,2
1  A(IPTS)=1.
  GO TO 3
2  K=IPT+ISTAR
  A(K)=X(IPTS)**(JORD-1)
3  CONTINUE
  DO 25 II=1,M
    Z(II)=Y(II)
25 CONTINUE
  CALL LLSQ (A,Z,M,IORD,1,C,IPIV,0.00001,IER,AUX)
  IF(IER)21,20,24
20 JJ=IORD-1
  WRITE(6,10)JJ
10 FORMAT('1'////////,7X,'LEAST SQUARES CURVE FIT OF ORDER '
1,I5//20X,'C
2EFFICIENTS -CO, C1,----,CN'//)
  WRITE(6,11) (C(K),K=1,IORD)
11 FORMAT(10X,E16.8/)
  IF(COMP)4,7,4
4  WRITE(6,12)
12 FORMAT(7X,'COMPARISON OF DATA AND FITTED CURVE'//)
1  X
1  Y Y CALC DIFFERENCE'//)
DO 6 I=1,M
  SUM=C(1)
DO 5 J=2,IORD
  SUM=SUM+C(J)*X(I)**(J-1)
5 CONTINUE
  VARY=Y(I)-SUM
  WRITE(6,13)X(I),Y(I),SUM,VARY
13 FORMAT(5X,4E16.8/)
6 CONTINUE
7  VAR(IORD)=AUX(1)/(M-1)
  WRITE(6,14)VAR(IORD)
14 FORMAT(7X,'CURVE FIT VARIANCE = ',E16.8//)
  IF(ABS(VAR(IORD))-ABS(VAR(IORD-1)))30,8,8
30 DO 31 I=1,IORD
  CS(I)=C(I)
31 CONTINUE
  IORDS=IORD
8 CONTINUE
DO 33 I=1,IORDS
  C(I)=CS(I)
33 CONTINUE
  N=IORDS
  JJ=IORDS-1
```


STAND

C

```
      WRITE(6,32)JJ
32  FORMAT('1'////////,7X,'BEST FIT POLYNOMIAL OF ORDER',I5/
      1/7X,'COEFFIC
      1ENTS CO TO CN'/)
      WRITE(6,11)(C(I),I=1,IORDS)
      YI=C(1)*X(15)
      K=N
      DO 203 I=2,K
      YI=YI+(C(I)*X(15)**I)/I
203  CONTINUE
      YZ=YI
      WRITE(87'2)YZ
      WRITE(6,354)YZ
354  FORMAT('0',10X,'AREA UNDER THE CURVE =',F10.5,2X
      1,'ATMOSP** (-2)')
      WRITE(6,15)
      15  FORMAT(20X,'FINIS')
      RETURN
      21  IF(IER+1)22,23,24
      22  WRITE(6,16)
      16  FORMAT('    MAX ORDER SPEC GREATER THAN NUMBER OF DATA
      1 POINTS')
      RETURN
      23  WRITE(6,18)
      18  FORMAT('    ZERO - MATRIX A')
      RETURN
      24  WRITE(6,17)
      17  FORMAT('    MATRIX OF RANK LESS THAN N')
      RETURN
      END
```


RNPLT

Subroutine RNPLT

C

C

```
EXTERNAL STAND
DIMENSION LX(10),LY(10)
COMMON X(40),Y(40),N,ID,IS,IG,IL,IT,IB,IU,IR,IP,XMAX
1,XMIN,NCYCX,
1 YMAX,YMIN,NCYCY,NFILX,NFILY,NPTS,IND
  DEFINE FILE 101(40,40,U,J1),102(40,40,U,J2)
  DATA LX/'FR','C ','PO','RE',' V','OL',' H','G ','IN'
1,'J.'/
  DATA LY/'RE','CI','P.',' ','PR','ES',' ','S','QR','
1 '/'
  CALL NWPLT(X,Y,N,ID,IS,IG,IL,IT,IB,IU,IR,IP,XMAX,XMIN
1,NCYCX,YMAX,
4YMIN,NCYCY,LX,LY,NFILX,NFILY,NPTS)
  WRITE(6,1111)
1111 FORMAT('  END OF PLOT ')
  CALL CHAIN (STAND)
  END
```


CHAUD

Subroutine CHAUD

C

C

```
EXTERNAL RNPLT
DIMENSION ARRAY(4)
COMMON X(40),Y(40),N,ID,IS,IG,IL,IT,IB,IU,IR,IP,XMAX
1,XMIN,NCYCX,
1 YMAX,YMIN,NCYCY,NFILX,NFIFY,NPTS,IND
EQUIVALENCE (ARRAY(1),AVVLB),(ARRAY(2),AVPRA)
1,(ARRAY(3),PPV)
1,(ARRAY(4),RPS)
DEFINE FILE 88(30,30,U,I88)
IND=1
100 ILOC=2
DO 803 J=1,15
ILOC=ILOC+1
READ(88,ILOC)ARRAY
X(J)=PPV
Y(J)=RPS
803 CONTINUE
N=15
ID=2
IS=1
IG=1
IL=1
IT=1
IB=1
IU=1
IR=1
IP=1
CALL CHAIN (RNPLT)
END
```


STILL

Subroutine STILL

C

C

```
EXTERNAL CMPLT
DIMENSION C(11),X1(100),Y1(100)
COMMON X(40),Y(40),N,ID,IS,IG,IL,IT,IB,IU,IR,IP,XMAX
1,XMIN,NCYCX,
1 YMAX,YMIN,NCYCY,NFILX,NFILY,NPTS,IND
DEFINE FILE 101(40,40,U,J1),102(40,40,U,J2),87(20,20,U
1,I87)
GO TO (100,200),IND
200 CALL VIAQ
100 IND=2
COMP=1.
M=15
N1=4
CALL CURVE (M,X,Y,N1,C,COMP)
NN=100
DO 2 I=1,NN
X1(I)=XMIN+(I-1)*(XMAX-XMIN)/(NN-1)
Y1(I)=C(1)
DO 3 J=1,N1
Y1(I)=Y1(I)+C(J+1)*X1(I)**J
3 CONTINUE
IF(Y1(I)-YMIN)4,2,5
4 Y1(I)=YMIN
GO TO 2
5 IF(Y1(I)-YMAX)2,2,6
6 Y1(I)=YMAX
2 CONTINUE
WRITE(101'1')(X1(I),I=1,NN)
WRITE(102'1')(Y1(I),I=1,NN)
NFILX=101
NFILY=102
IR=2
N=20
NPTS=NN
IS=2
IU=IG+1
IP=-1
CALL CHAIN (CMPLT)
END
```


STILL

C

C

C*****

C*****

C

C SUBROUTINE CURVE (M,X,Y,N,C,COMP)

C

C PURPOSE

C TO FIT A GIVEN SET OF POINTS WITH THE BEST FIT
C POLYNOMIAL

C WHOSE ORDER WILL BE FROM TWO TO THAT SPECIFIED BY
C THE USER

C WITH A PRESENT MAXIMUM OF FOUR

C

C PARAMETERS

C M - NUMBER OF DATA POINTS TO BE FITTED

C X - VECTOR OF M INDEPENDENT VALUES

C Y - VECTOR OF M DEPENDENT VALUES

C N - ENTER THE MAXIMUM ORDER OF POLYNOMIAL YOU
C WANT TRIED

C TO A MAXIMUM OF TEN

C - RETURNS THE ORDER OF THE BEST FIT
C POLYNOMIAL BETWEEN

C TWO AND N.

C C - VECTOR OF DIMENSION N+1 WHICH RETURNS THE
C N+1

C COEFFICIENTS OF THE BEST FIT POLYNOMIAL,
C $Y=C_0+C_1*X+C_2*X**2+C_3*X**3+.....$

C COMP - SET TO 1. - PRINTS OUT A COMPARISON OF THE
C GIVEN POINTS

C AND THE CORRESPONDING ONES ON THE
C POLYNOMIAL

C SET TO 0. - NO COMPARISON

C

C *** IMPORTANT NOTE *** THE MATRIX A IN THE
C **DIMENSION

C STATEMENT OF THIS SUBROUTINE MUST BE DIMENSIONED
C TO M*N

C

C

C*****

C*****

C

C

SUBROUTINE CURVE(M,X,Y,N,C,COMP)

DIMENSION X(1),Y(1),C(1),A(140),AUX(20),Z(25)

DIMENSION CS(11),VAR(10)

VAR(1)=1.E25

N1=N+1

STILL

C

```
DO 8 IORD=2,N1
DO 3 JORD=1,IORD
  ISTAR =(JORD-1)*M
DO 3 IPTS=1,M
  IF(JORD-1)2,1,2
1  A(IPTS)=1.
  GO TO 3
2  K=IPTS+ISTAR
  A(K)=X(IPTS)**(JORD-1)
3  CONTINUE
DO 25 II=1,M
  Z(II)=Y(II)
25 CONTINUE
  CALL LLSQ (A,Z,M,IORD,1,C,IPIV,0.00001,IER,AUX)
  IF(IER)21,20,24
20  JJ=IORD-1
  WRITE(6,10)JJ
10  FORMAT('1'////////,7X,'LEAST SQUARES CURVE FIT OF ORDER '
1,15//20X,'C
2EFFICIENTS -CO, C1,----,CN'//)
  WRITE(6,11) (C(K),K=1,IORD)
11  FORMAT(10X,E16.8/)
  IF(COMP)4,7,4
4  WRITE(6,12)
12  FORMAT(7X,'COMPARISON OF DATA AND FITTED CURVE'//)
1  X
1  Y          Y CALC          DIFFERENCE'//)
DO 6 I=1,M
  SUM=C(1)
DO 5 J=2,IORD
  SUM=SUM+C(J)*X(I)**(J-1)
5  CONTINUE
  VARY=Y(I)-SUM
  WRITE(6,13)X(I),Y(I),SUM,VARY
13  FORMAT(5X,4E16.8/)
6  CONTINUE
7  VAR(IORD)=AUX(1)/(M-1)
  WRITE(6,14)VAR(IORD)
14  FORMAT(7X,'CURVE FIT VARIANCE = ',E16.8//)
  IF(ABS(VAR(IORD))-ABS(VAR(IORD-1)))30,8,8
30  DO 31 I=1,IORD
  CS(I)=C(I)
31  CONTINUE
  IORDS=IORD
8  CONTINUE
DO 33 I=1,IORDS
  C(I)=CS(I)
33  CONTINUE
  N=IORDS
  JJ=IORDS-1
```


STILL

C

```
      WRITE(6,32)JJ
32  FORMAT('1'//////,7X,'BEST FIT POLYNOMIAL OF ORDER',I5/
      1/7X,'COEFFIC
      IENTS CO TO CN'/)
      WRITE(6,11)(C(I),I=1,IORDS)
      WRITE(6,15)
15  FORMAT(20X,'FINIS')
      RETURN
21  IF(IER+1)22,23,24
22  WRITE(6,16)
16  FORMAT('    MAX ORDER SPEC GREATER THAN NUMBER OF DATA
      1 POINTS')
      RETURN
23  WRITE(6,18)
18  FORMAT('    ZERO - MATRIX A')
      RETURN
24  WRITE(6,17)
17  FORMAT('    MATRIX OF RANK LESS THAN N')
      RETURN
      END
```


MAHMD

Subroutine MAHMD

C

C

```
EXTERNAL CMPLT
DIMENSION ARRAY(4)
COMMON X(40),Y(40),N,ID,IS,IG,IL,IT,IB,IU,IR,IP,XMAX
1,XMIN,NCYCX,
1 YMAX,YMIN,NCYCY,NFILX,NFILY,NPTS,IND
EQUIVALENCE (ARRAY(1),AVVLB),(ARRAY(2),AVPRA)
1,(ARRAY(3),PPV)
1,(ARRAY(4),RPS)
DEFINE FILE 88(30,30,U,I88)
IND=1
100 ILOC=2
DO 803 J=1,15
ILOC=ILOC+1
READ(88'ILOC)ARRAY
X(J)=PPV
Y(J)=AVPRA
803 CONTINUE
N=15
ID=2
IS=1
IG=1
IL=1
IT=1
IB=1
IU=1
IR=1
IP=1
CALL CHAIN (CMPLT)
END
```


CMPLT

Subroutine CMPLT

C

C

```
EXTERNAL STILL
DIMENSION LX(10),LY(10)
COMMON X(40),Y(40),N,ID,IS,IG,IL,IT,IB,IU,IR,IP,XMAX
1,XMIN,NCYCX,
1 YMAX,YMIN,NCYCY,NFILX,NFILY,NPTS,IND
DEFINE FILE 101(40,40,U,J1),102(40,40,U,J2)
DATA LX/'FR','C ','PO','RE','V','OL','H','G ','IN'
1,'J.'/
DATA LY/'PR','ES',' ','IN',' ','AT','MO','SP',' ','
1 '/'
CALL NWPLT(X,Y,N,ID,IS,IG,IL,IT,IB,IU,IR,IP,XMAX,XMIN
1,NCYCX,YMAX,
4YMIN,NCYCY,LX,LY,NFILX,NFILY,NPTS)
WRITE(6,1111)
1111 FORMAT('  END OF PLOT ')
CALL CHAIN (STILL)
END
```


A P P E N D I X I V

MERCURY CAPILLARY PRESSURE DATA FROM
ON-LINE PURCELL CELL FOR CORES 1 THROUGH 9

Table IV-1
Mercury Capillary Pressure Data
Core 1

Bulk Volume = 13.277 c c

Porosity = 0.320

Pore Volume = 4.248 c c

Cum. Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.29685	0.58169	0.06986	2.95540
0.88634	0.73334	0.20860	1.85947
1.17405	0.80157	0.27632	1.55638
1.44066	0.88798	0.33907	1.26821
1.57713	0.96738	0.37119	1.06857
2.06674	1.98554	0.48642	0.25365
2.25807	3.93985	0.53145	0.06442
2.30802	4.98489	0.54321	0.04024
2.35093	5.99311	0.55331	0.02784
2.44730	10.50940	0.57599	0.00905
2.54508	18.00583	0.59900	0.00308
2.60698	25.48083	0.61357	0.00154
2.67100	37.23087	0.62864	0.00072
2.73572	54.07787	0.64387	0.00034
2.79480	71.07092	0.65777	0.00019

Area Under the Curve = 0.89374 atm.⁻²

Calculated Permeability = 0.66 x Porosity x Area Under Curve x 10000.0 m d
= 1887.580 millidarcys

Table IV-2

Mercury Capillary Pressure Data

Core 2

Bulk Volume = 13.253 c c

Porosity = 0.293

Pore Volume = 3.883 c c

Cum.Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.51492	0.66531	0.13259	2.25918
1.11989	0.80638	0.28838	1.53786
1.36469	0.89519	0.35142	1.24785
1.81068	1.41274	0.46627	0.50104
2.09839	2.96974	0.54035	0.11338
2.19336	4.25453	0.56481	0.05524
2.32209	7.69949	0.59796	0.01686
2.45153	16.95021	0.63129	0.00348
2.54719	29.55916	0.65592	0.00114
2.59573	39.37716	0.66842	0.00064
2.63442	51.20121	0.67839	0.00038
2.67522	64.29318	0.68889	0.00024
2.70758	76.13087	0.69723	0.00017
2.72587	84.20184	0.70194	0.00014
2.74416	89.11375	0.70665	0.00012

Area Under the Curve = 0.79929 atm.⁻²

Calculated Permeability = 0.66 x Porosity x Area Under Curve x 10000.0 m d
= 1545.667 millidarcys .

Table IV-3

Mercury Capillary Pressure Data

Core 3

Bulk Volume = 13.697 c c

Porosity = 0.255

Pore Volume = 3.492 c c

Cum.Vol.Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.20400	0.59513	0.05840	2.82342
0.81741	0.73510	0.23402	1.85057
1.24370	0.86065	0.35606	1.35001
1.41815	0.97115	0.40601	1.06029
1.77692	1.70047	0.50872	0.34582
1.96263	3.08822	0.56189	0.10485
2.04423	4.25245	0.58525	0.05529
2.16733	7.72260	0.62049	0.01676
2.26371	14.65396	0.64809	0.00465
2.38610	30.41611	0.68313	0.00108
2.43534	43.13803	0.69723	0.00053
2.48389	58.45029	0.71112	0.00029
2.52609	72.67189	0.72321	0.00018
2.55141	84.52126	0.73046	0.00013
2.58237	93.64785	0.73932	0.00011

Area Under the Curve = 0.92970 atm.⁻²

Calculated Permeability = 0.66 x Porosity x Area Under Curve x 10000.0 m d
= 1564.695 millidarcys

Table IV-4

Mercury Capillary Pressure Data

Core 4

Bulk Volume = 13.324 c c

Porosity = 0.241

Pore Volume = 3.211 c c

Cum. Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.17726	0.54962	0.05520	3.31035
0.48721	0.61124	0.15172	2.67655
1.24651	0.83131	0.38817	1.44701
1.54055	0.96946	0.47974	1.06399
1.92886	1.57764	0.60067	0.40177
2.14693	2.87567	0.66858	0.12092
2.24893	4.25453	0.70034	0.05524
2.36922	7.32996	0.73780	0.01861
2.51624	16.35229	0.78358	0.00373
2.64497	31.26333	0.82367	0.00102
2.69281	44.42931	0.83857	0.00050
2.74627	57.54269	0.85522	0.00030
2.79059	71.90451	0.86902	0.00019
2.82998	84.62060	0.88129	0.00013
2.86586	95.81556	0.89246	0.00010

Area Under the Curve = 1.19007 atm.⁻²

Calculated Permeability = 0.66 x Porosity x Area Under Curve x 10000.0 m d
= 1892.934 millidarcys

Table IV-5

Mercury Capillary Pressure Data

Core 5

Bulk Volume = 13.316 c c

Porosity = 0.205

Pore Volume = 2.729 c c

Cum.Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.12567	0.52326	0.04603	3.65228
0.35562	0.59980	0.13027	2.77963
0.47201	0.65980	0.17290	2.29707
0.70837	0.80326	0.25949	1.54984
1.05799	1.42659	0.38756	0.49136
1.28239	3.03934	0.46976	0.10825
1.35836	4.25453	0.49759	0.05524
1.47373	7.42955	0.53985	0.01811
1.60949	17.27157	0.58958	0.00335
1.67773	27.92315	0.61458	0.00128
1.74596	44.37869	0.63958	0.00050
1.78043	58.53793	0.65220	0.00029
1.81912	71.49163	0.66638	0.00019
1.84515	81.58616	0.67591	0.00015
1.87891	92.65649	0.68828	0.00011

Area Under the Curve = 0.87211 atm.⁻²

Calculated Permeability = 0.66 x Porosity x Area Under Curve x 10000.0 m d
= 1179.967 millidarcys

Table IV-6
Mercury Capillary Pressure Data
Core 6

Bulk Volume = 13.457 c c

Porosity = 0.225

Pore Volume = 3.027 c c

Cum.Vol Hg Injected c c	Pressure atm	Frc Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.08722	0.56260	0.02880	3.15937
0.46427	0.63737	0.15332	2.46159
0.81037	0.75496	0.26762	1.75449
1.12552	0.87565	0.37170	1.30418
1.27817	0.97128	0.42211	1.06001
1.65100	1.71170	0.54524	0.34130
1.83952	3.06498	0.60750	0.10644
1.90424	4.25453	0.62887	0.05524
2.00694	6.94044	0.66279	0.02075
2.16452	19.02248	0.71483	0.00276
2.23838	30.63036	0.73922	0.00106
2.28903	44.43904	0.75595	0.00050
2.32701	58.62559	0.76850	0.00029
2.36640	72.15772	0.78150	0.00019
2.40861	90.96596	0.79544	0.00012

Table IV-7
Mercury Capillary Pressure Data
Core 7

Bulk Volume = 13.141 c c

Porosity = 0.205

Pore Volume = 2.693 c c

Cum.Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.09496	0.58980	0.03524	2.87468
0.31022	0.64433	0.11515	2.40870
0.78575	0.81631	0.29167	1.50068
1.05025	0.91713	0.38985	1.18888
1.14311	0.97783	0.42432	1.04585
1.58276	1.80545	0.58752	0.30678
1.73541	3.07270	0.64419	0.10591
1.80716	4.25453	0.67082	0.05524
1.93027	7.75000	0.71652	0.01664
2.06603	17.92012	0.76691	0.00311
2.16100	32.45139	0.80217	0.00094
2.19969	46.23865	0.81653	0.00046
2.24964	62.87530	0.83507	0.00025
2.28833	79.71842	0.84943	0.00015
2.31716	92.34684	0.86013	0.00011

Table IV-8
Mercury Capillary Pressure Data
Core 8

Bulk Volume = 13.211 c c

Porosity = 0.263

Pore Volume = 3.474 c c

Cum. Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.09988	0.55228	0.02874	3.27854
0.26309	0.58074	0.07572	2.96508
0.92011	0.73569	0.26481	1.84761
1.25565	0.89246	0.36139	1.25551
1.39634	0.96693	0.40188	1.06957
1.73259	1.52427	0.49866	0.43040
1.98584	3.07998	0.57154	0.10541
2.06181	4.20298	0.59341	0.05660
2.17296	6.82605	0.62540	0.02146
2.37133	20.36245	0.68249	0.00241
2.45504	34.07961	0.70658	0.00086
2.50639	47.50656	0.72136	0.00044
2.54649	62.77207	0.73291	0.00025
2.59292	79.27242	0.74627	0.00015
2.63192	90.46971	0.75749	0.00012

Table IV-9
Mercury Capillary Pressure Data
Core 9

Bulk Volume = 13.289 c c

Porosity = 0.214

Pore Volume = 2.843 c c

Cum.Vol. Hg Injected c c	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.08652	0.54150	0.03042	3.41038
0.22932	0.57099	0.08063	3.06720
0.61059	0.65428	0.21469	2.33599
0.98694	0.70959	0.34702	1.98602
1.26832	0.96926	0.44596	1.06443
1.70375	1.86517	0.59907	0.28745
1.90142	3.53520	0.66857	0.08001
2.01890	6.14775	0.70988	0.02645
2.08713	9.95822	0.73387	0.01008
2.19617	19.93593	0.77221	0.00251
2.28059	34.16141	0.80190	0.00085
2.33686	51.43103	0.82168	0.00037
2.38470	70.58401	0.83850	0.00020
2.41354	80.01444	0.84864	0.00015
2.44449	90.43037	0.85953	0.00012

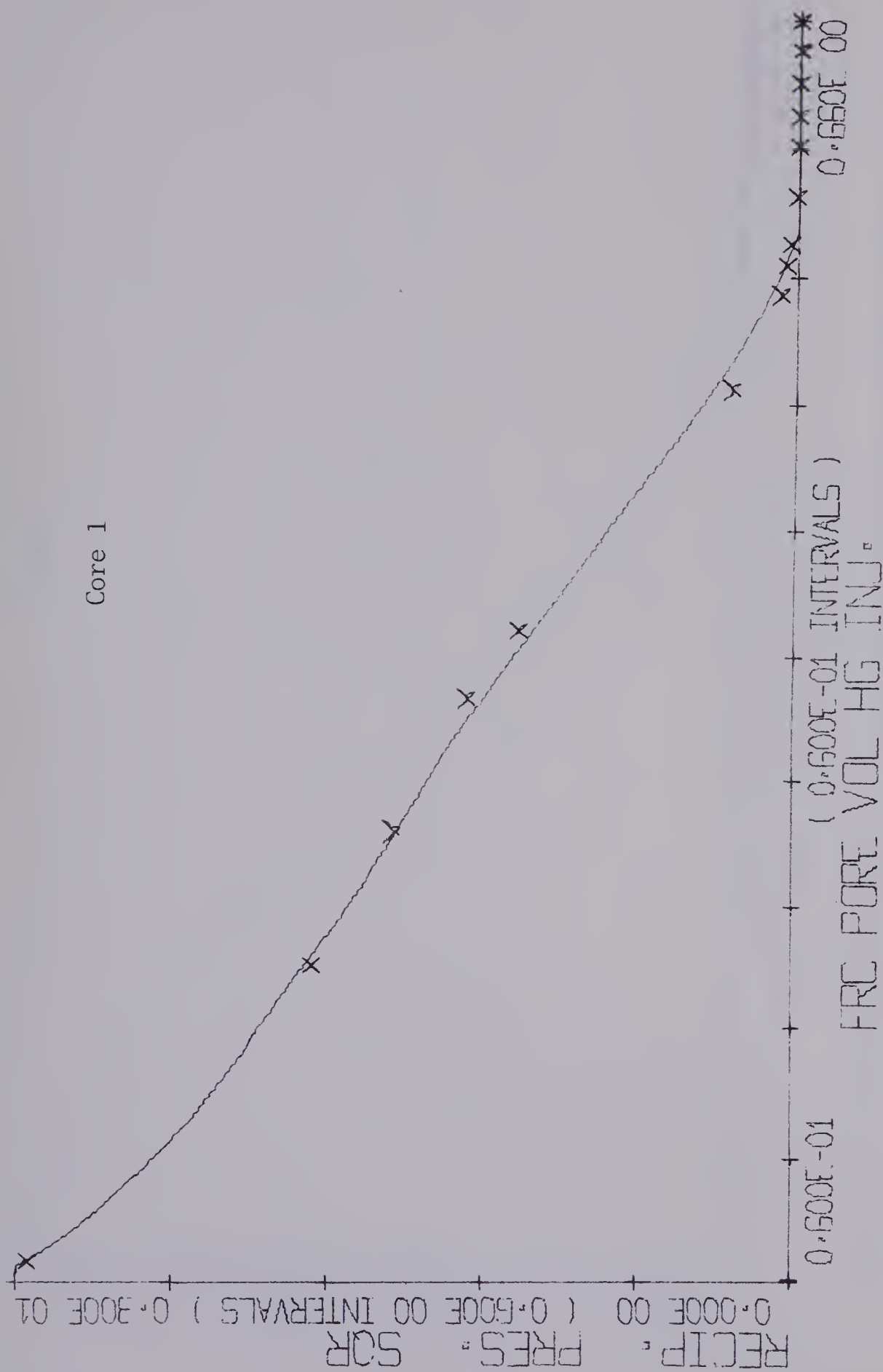


Figure IV-1. Fraction Saturation as a Function of Reciprocal of Square Capillary Pressure

Core 2

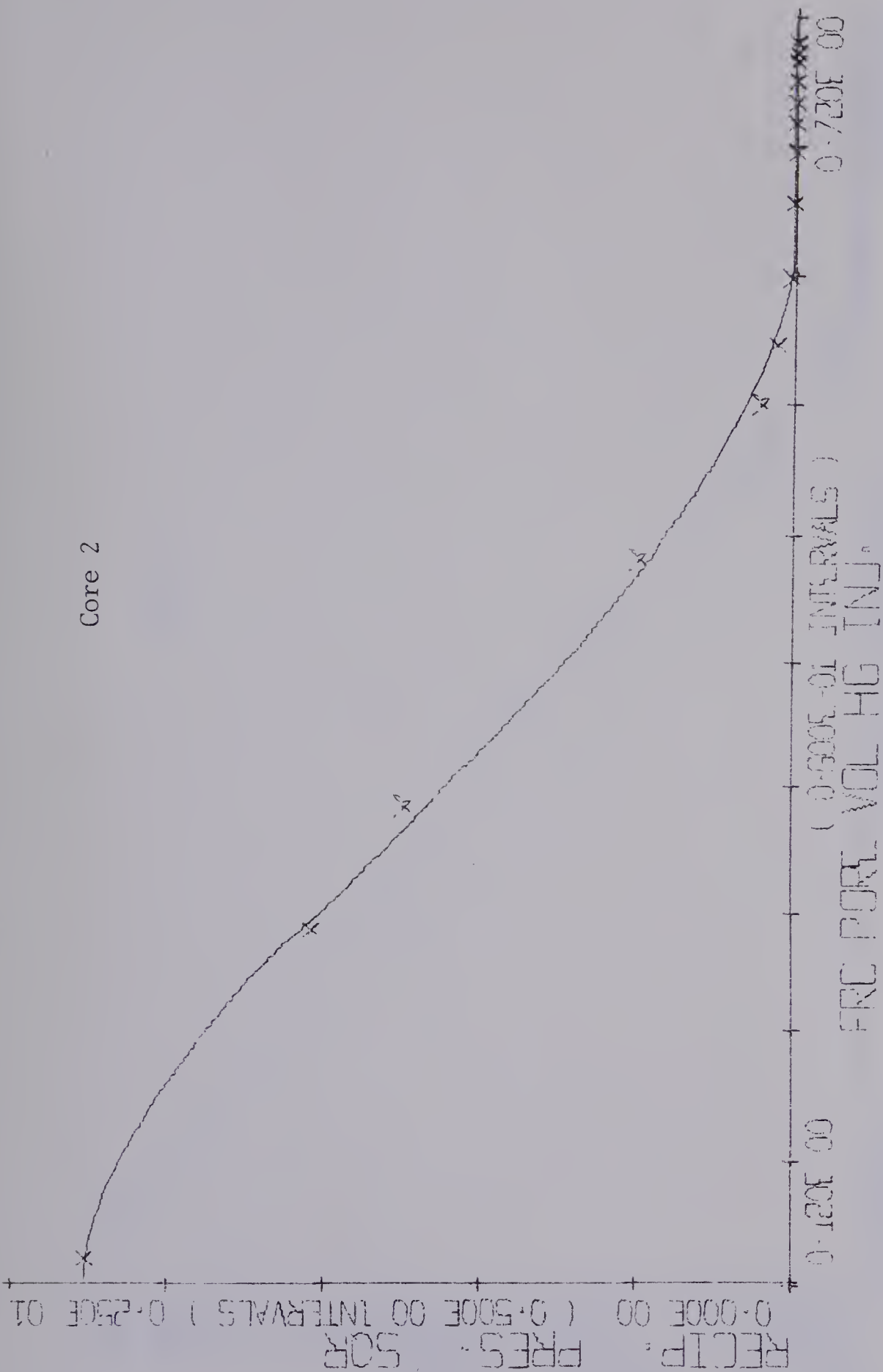


Figure IV-2. Fraction Saturation as a Function of Reciprocal of Square Capillary Pressure

Core 3

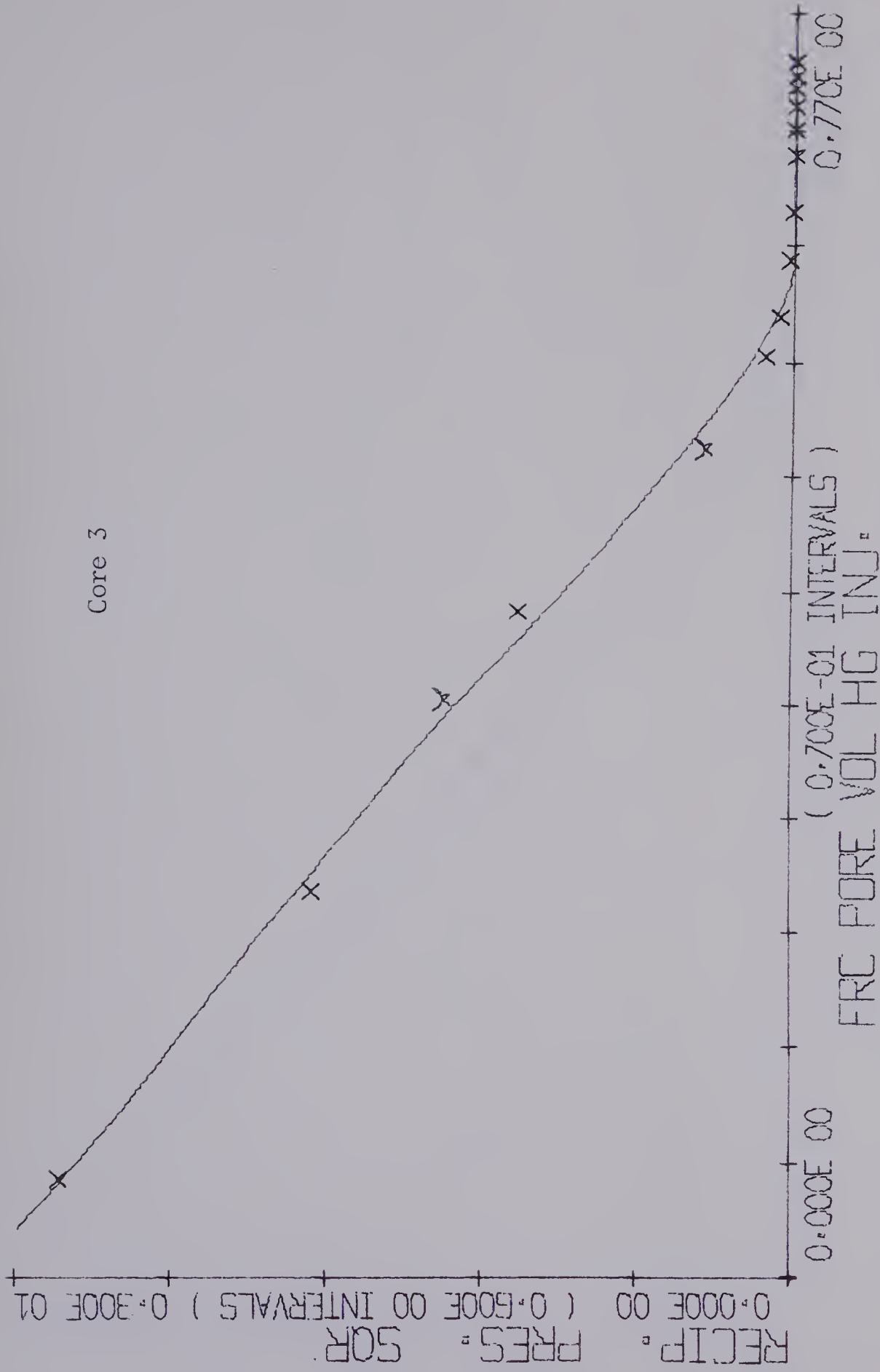


Figure IV-3. Fraction Saturation as a Function of Reciprocal of Square Capillary Pressure

Core 4

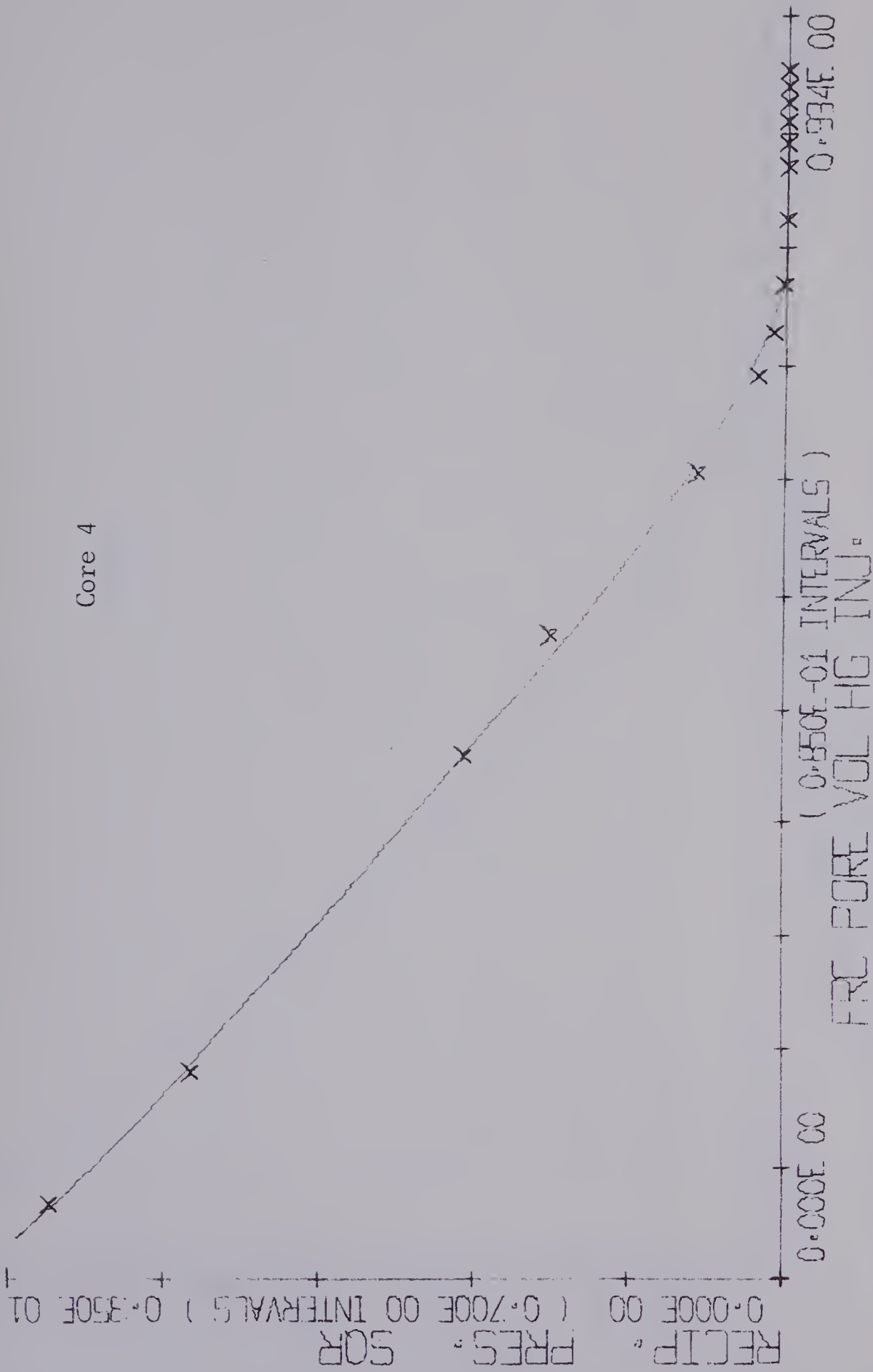


Figure IV-4. Fraction Saturation as a Function of Reciprocal of Square Capillary Pressure

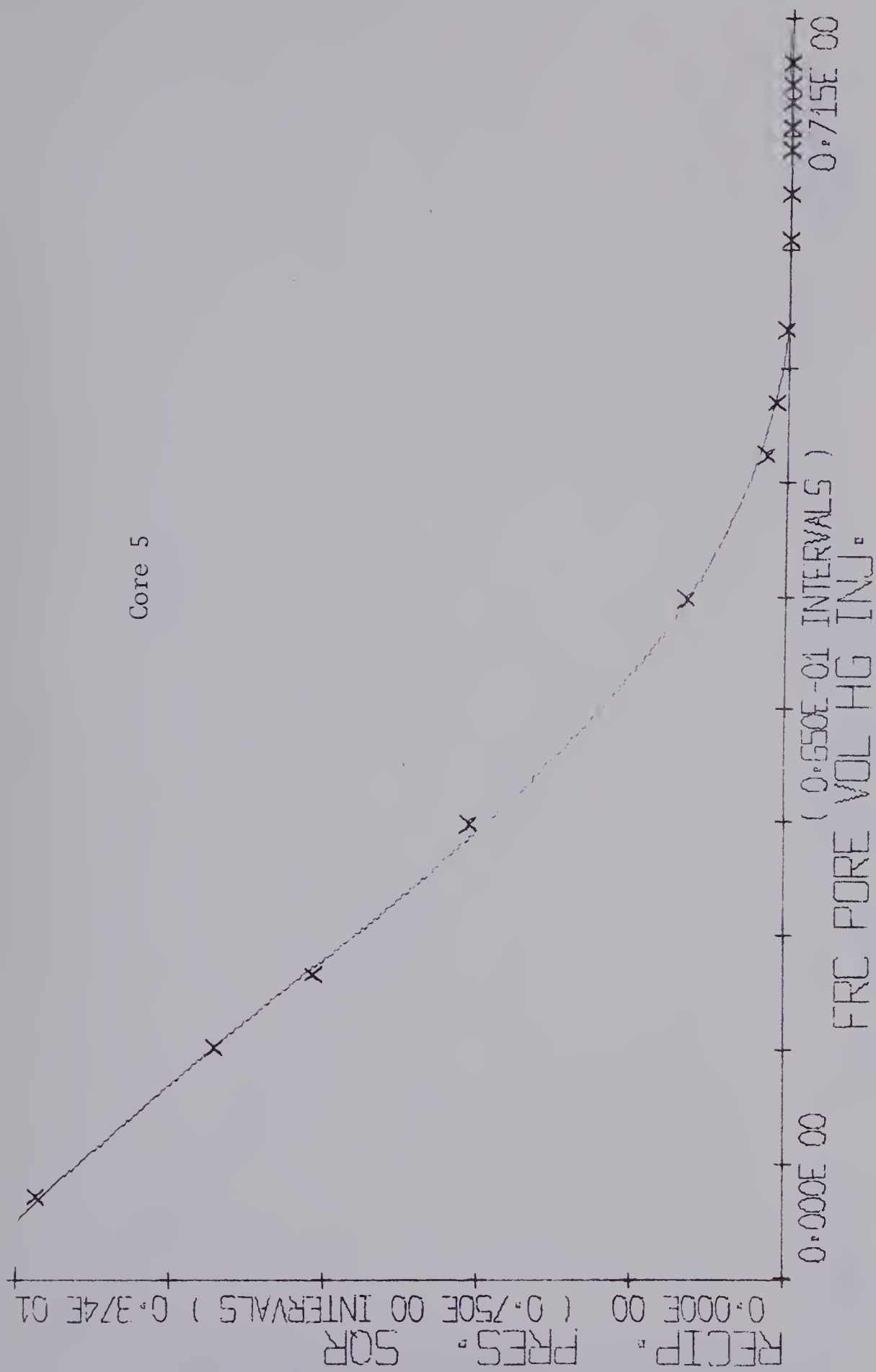


Figure IV-5. Fraction Saturation as a Function of Reciprocal of Square Capillary Pressure

Core 7

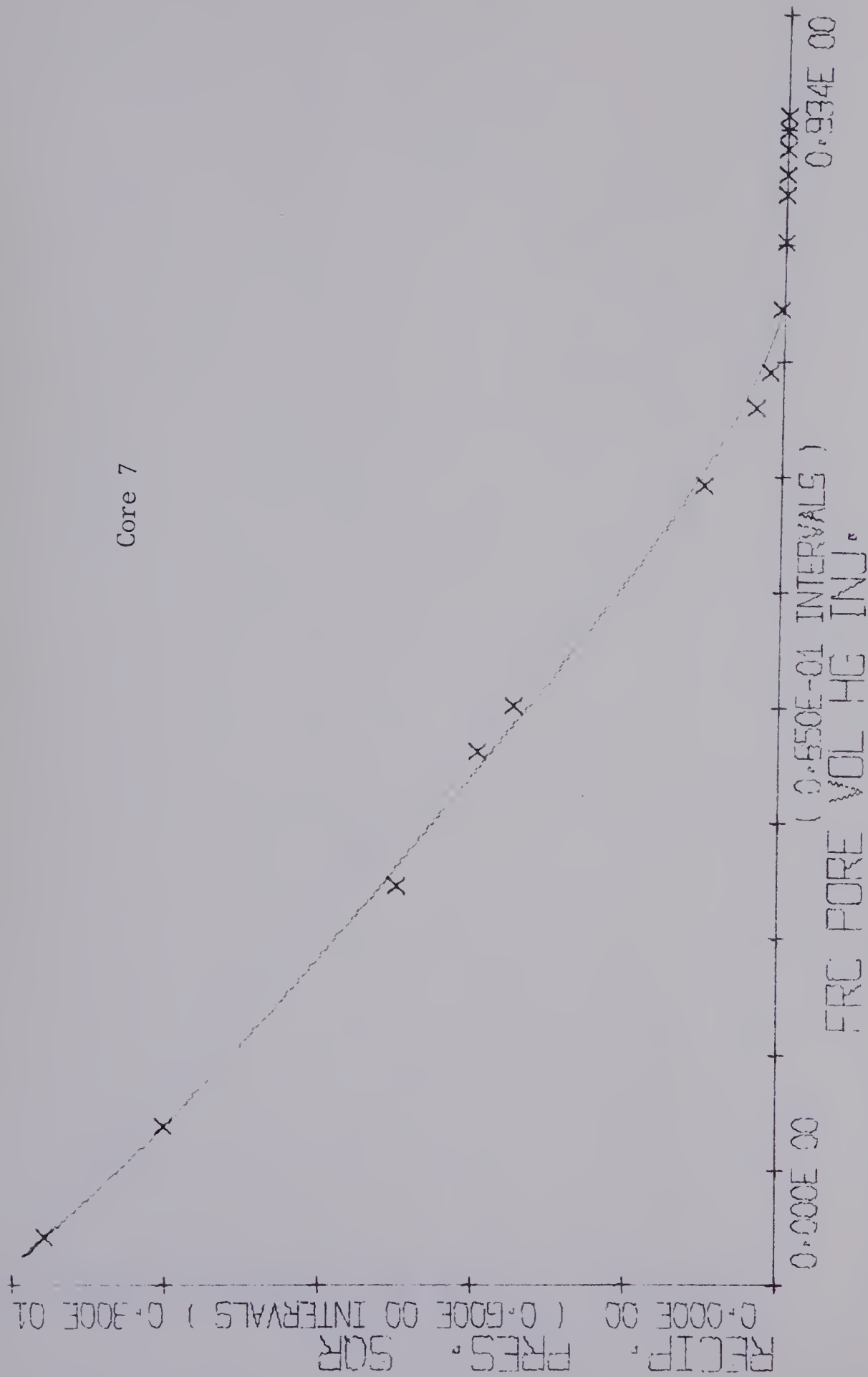


Figure IV-7. Fraction Saturation as a Function of Reciprocal of Square Capillary Pressure

Core 8

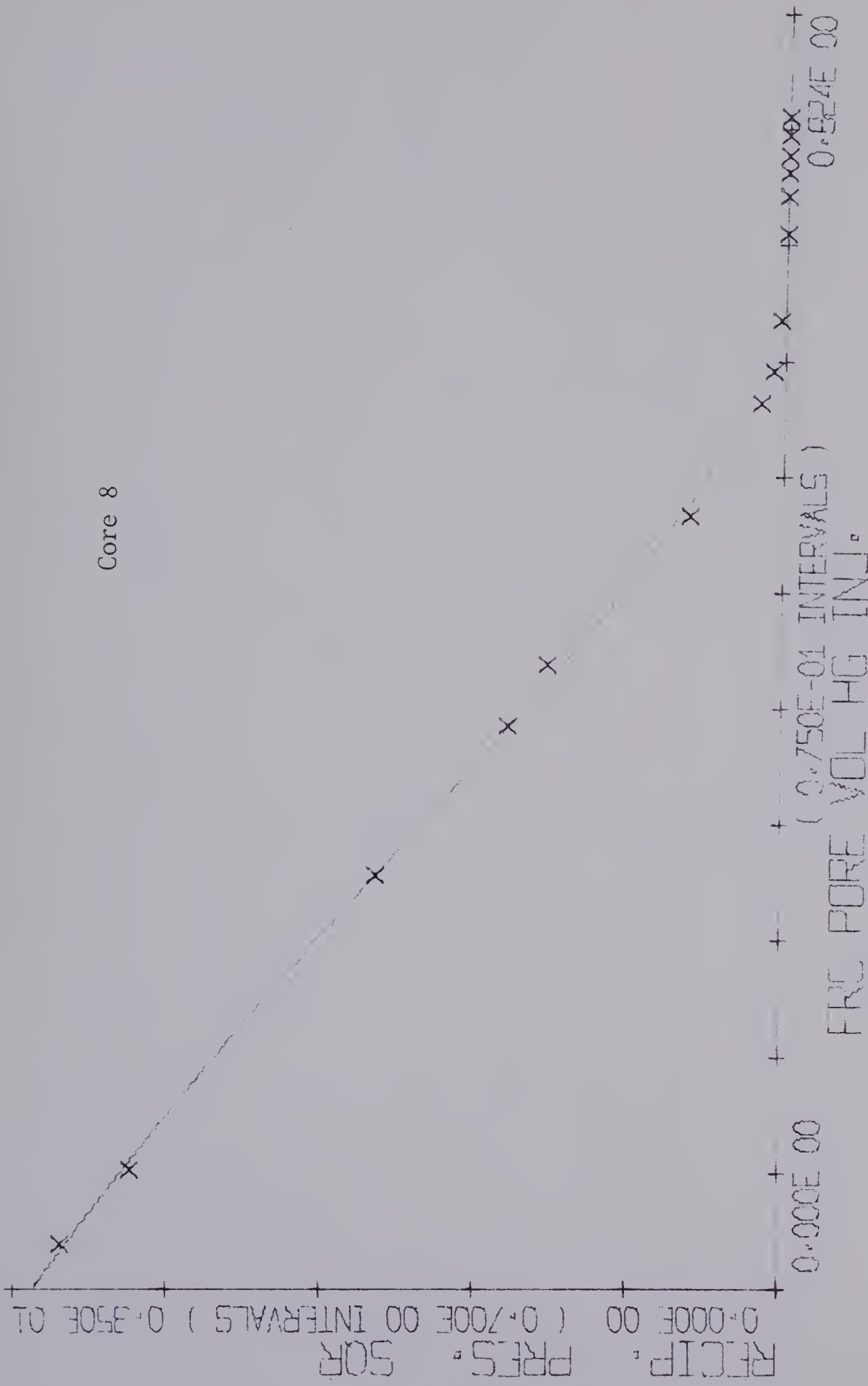


Figure IV-8. Fraction Saturation as a Function of Reciprocal of Square Capillary Pressure

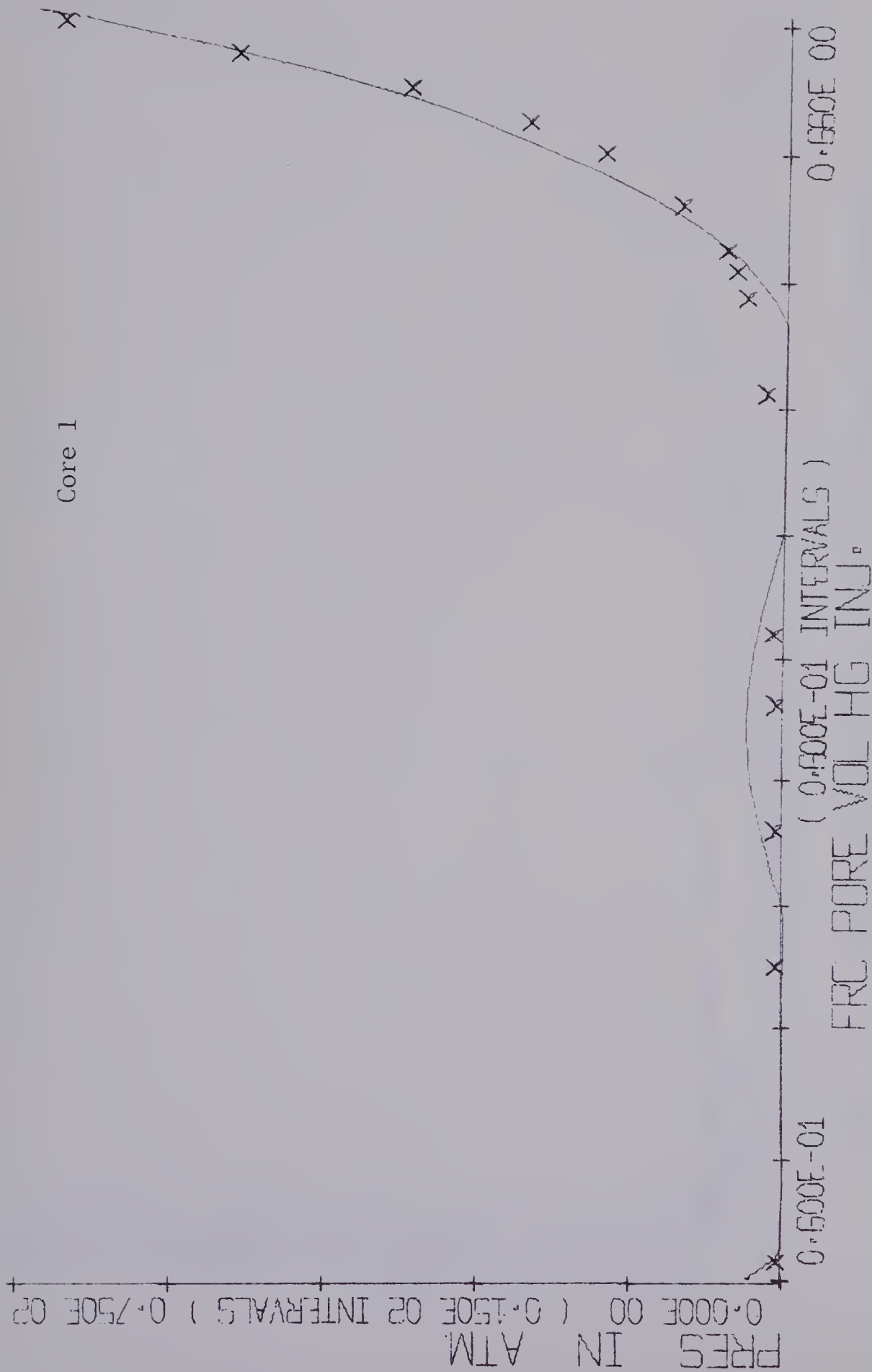


Figure IV-10. Fraction Saturation as a Function of Capillary Pressure

Core 2

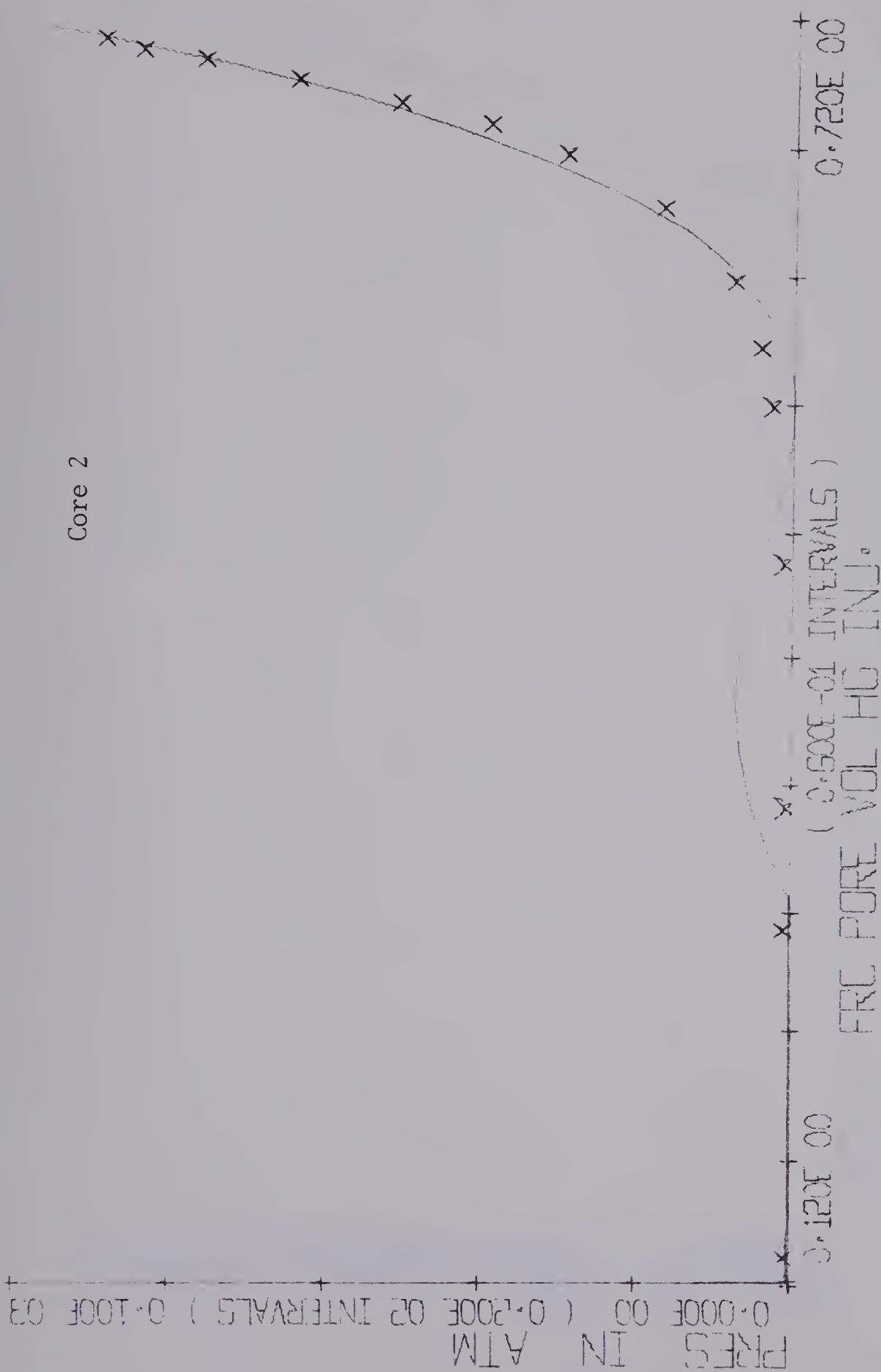


Figure IV-11. Fraction Saturation as a Function of Capillary Pressure

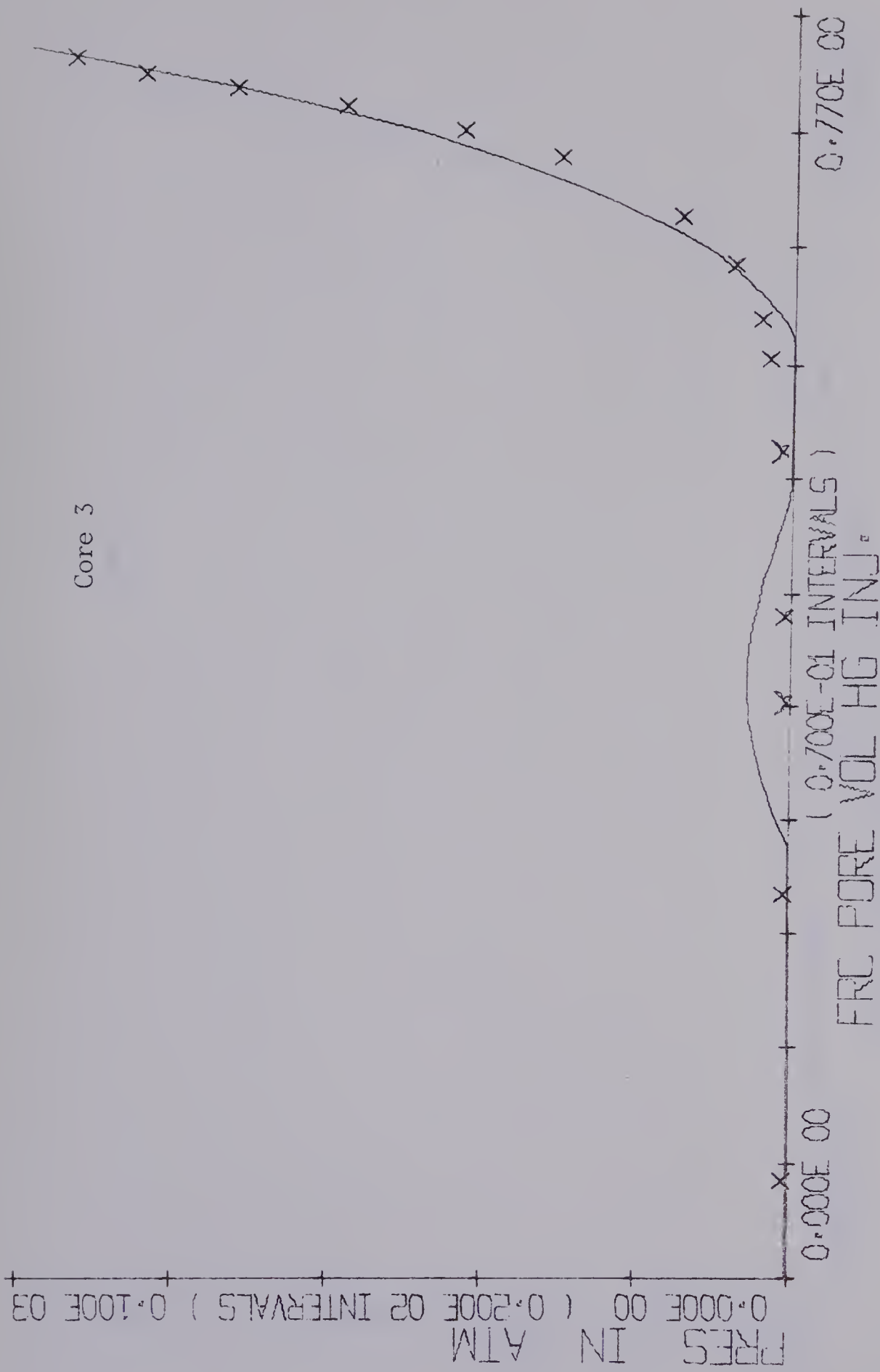


Figure IV-12. Fraction Saturation as a Function of Capillary Pressure

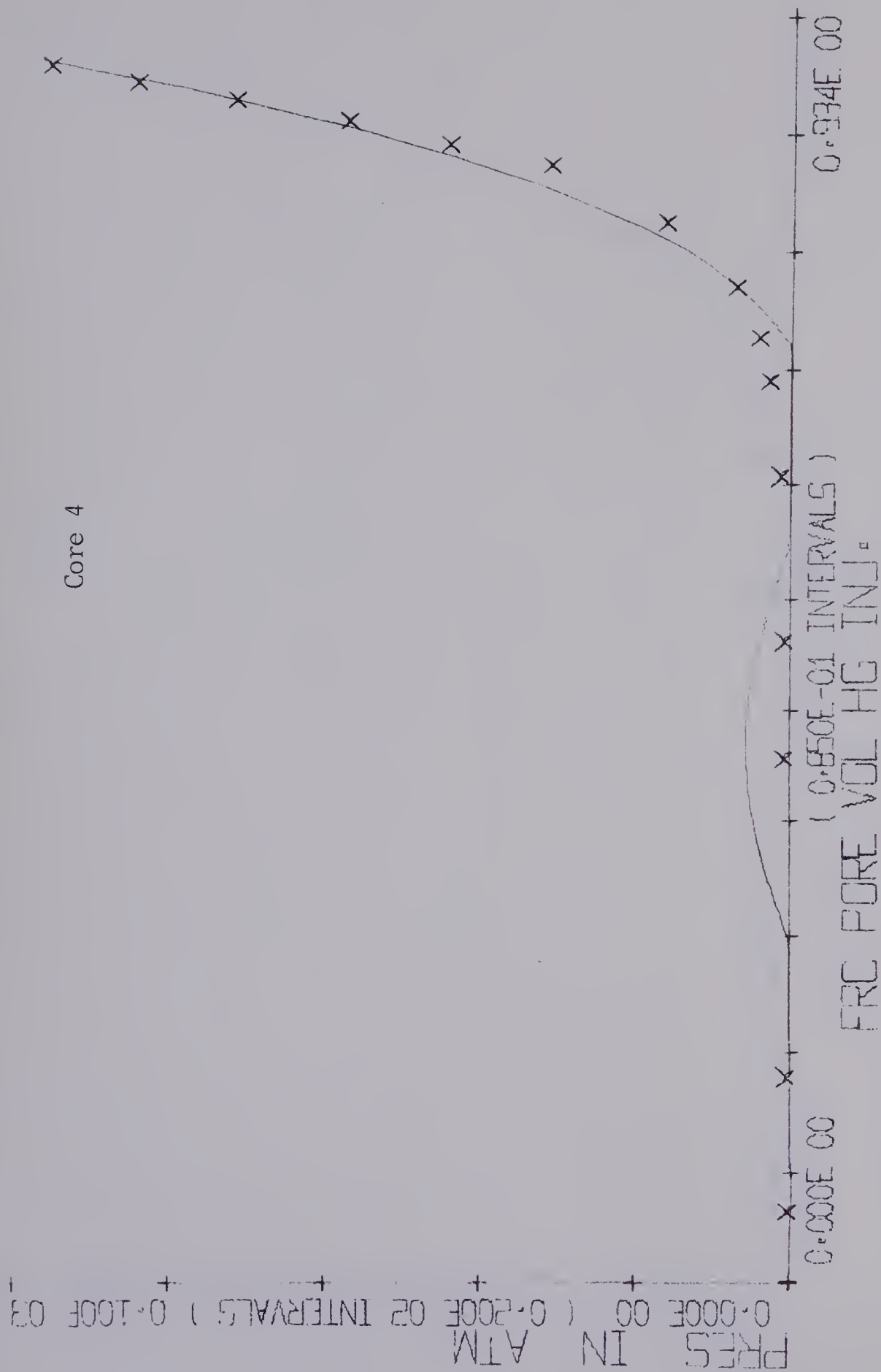


Figure IV-13. Fraction Saturation as a Function of Capillary Pressure

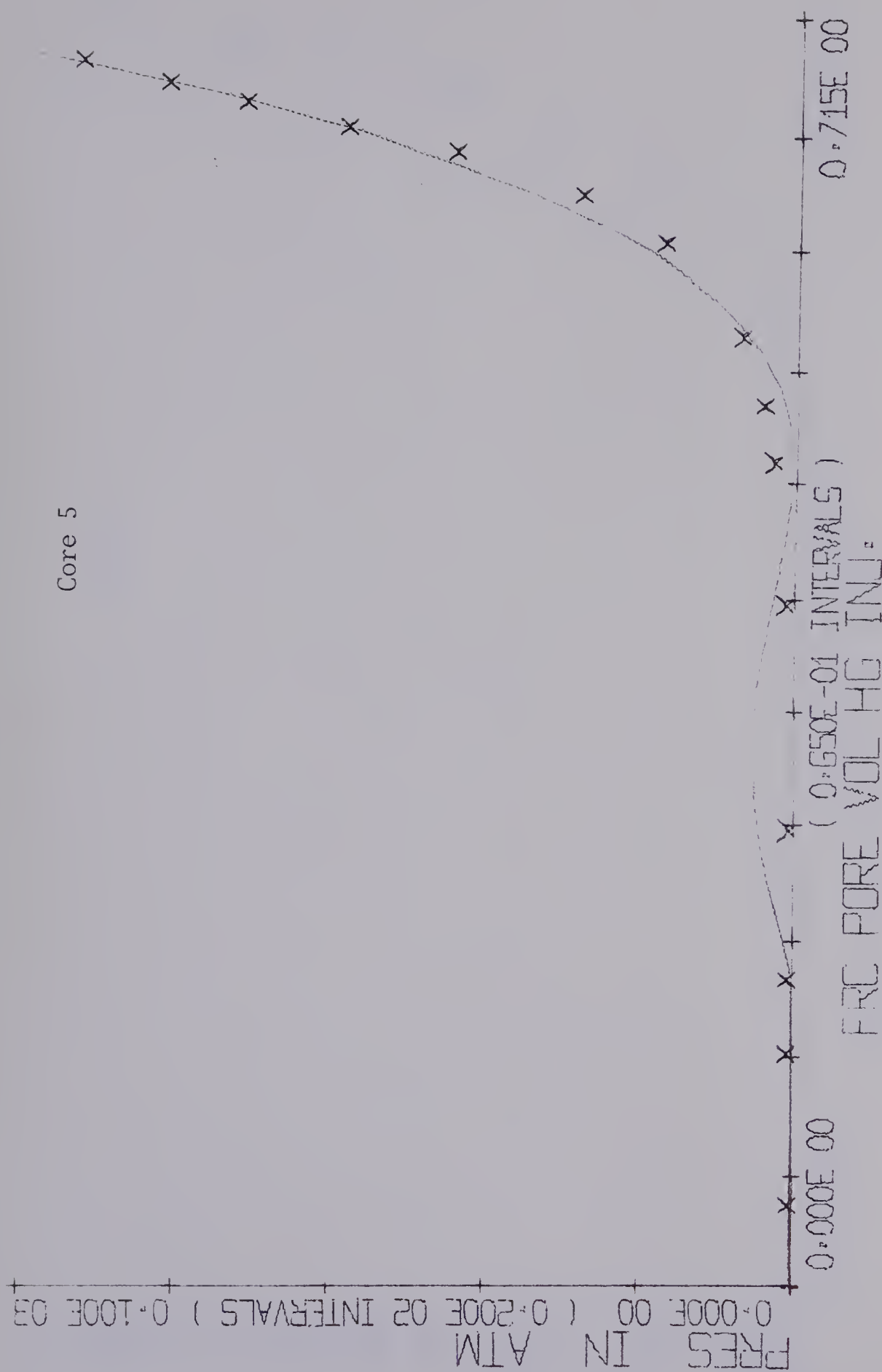


Figure IV-14. Fraction Saturation as a Function of Capillary Pressure

Core 6

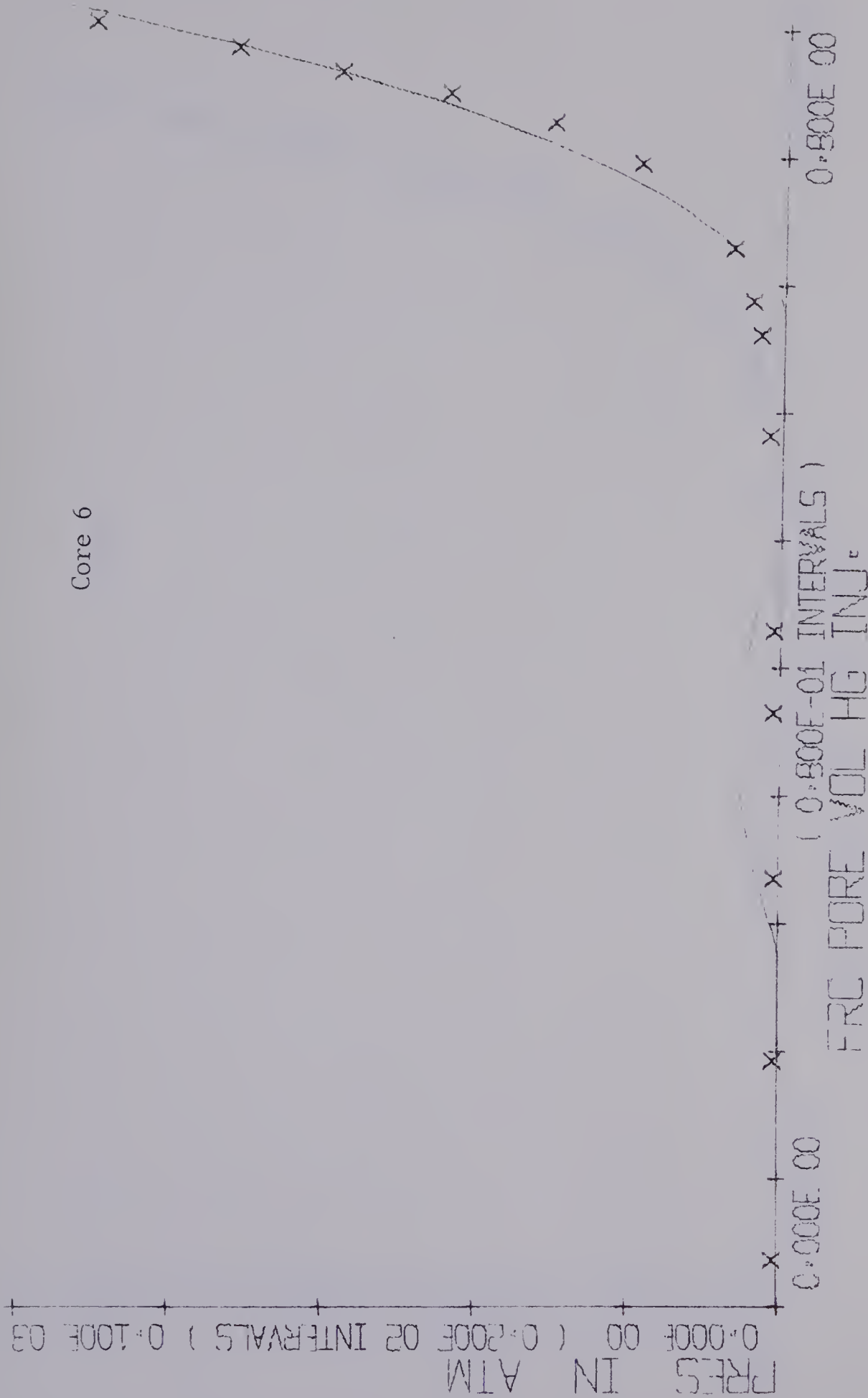


Figure IV-15. Fraction Saturation as a Function of Capillary Pressure

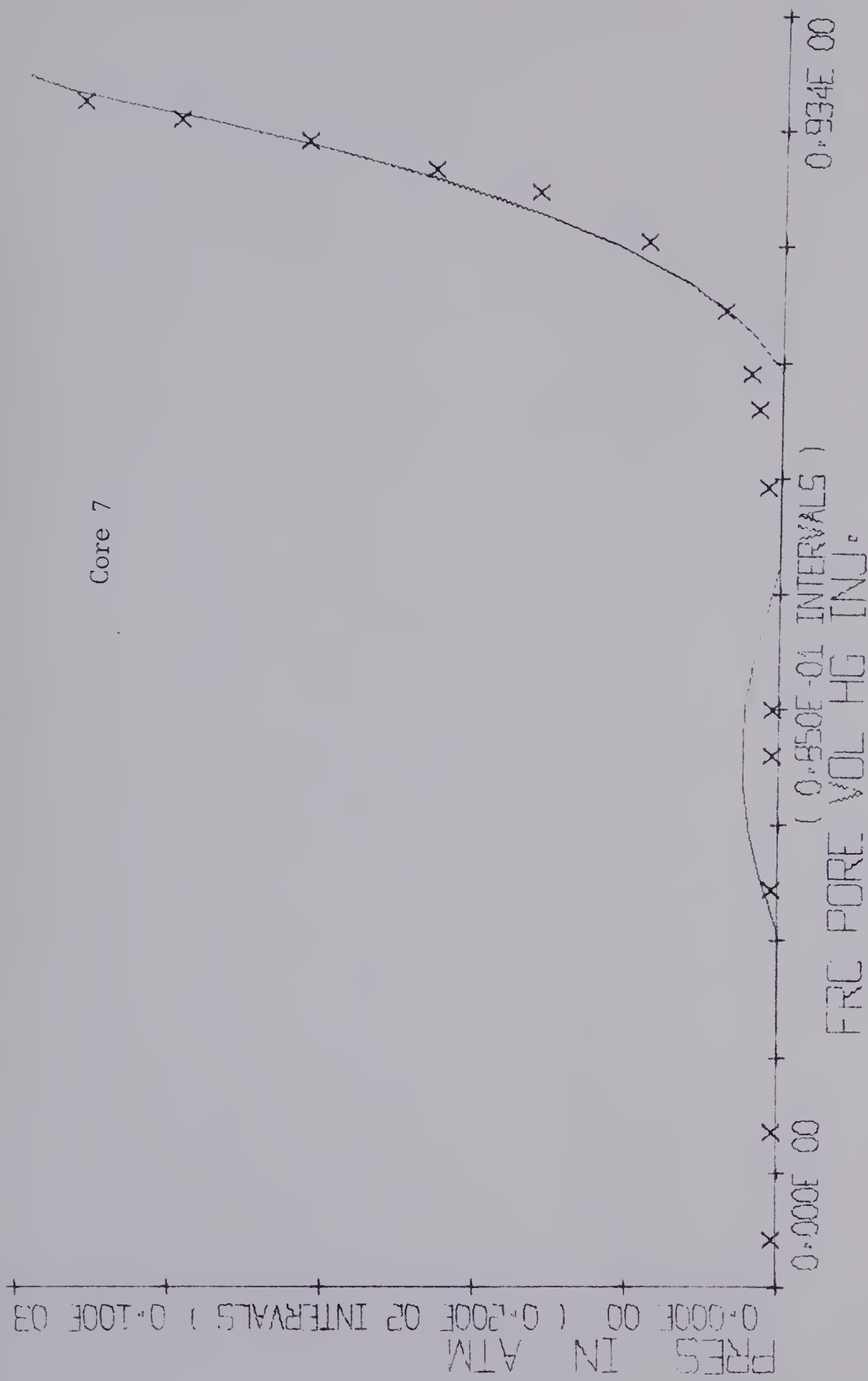


Figure IV-16. Fraction Saturation as a Function of Capillary Pressure

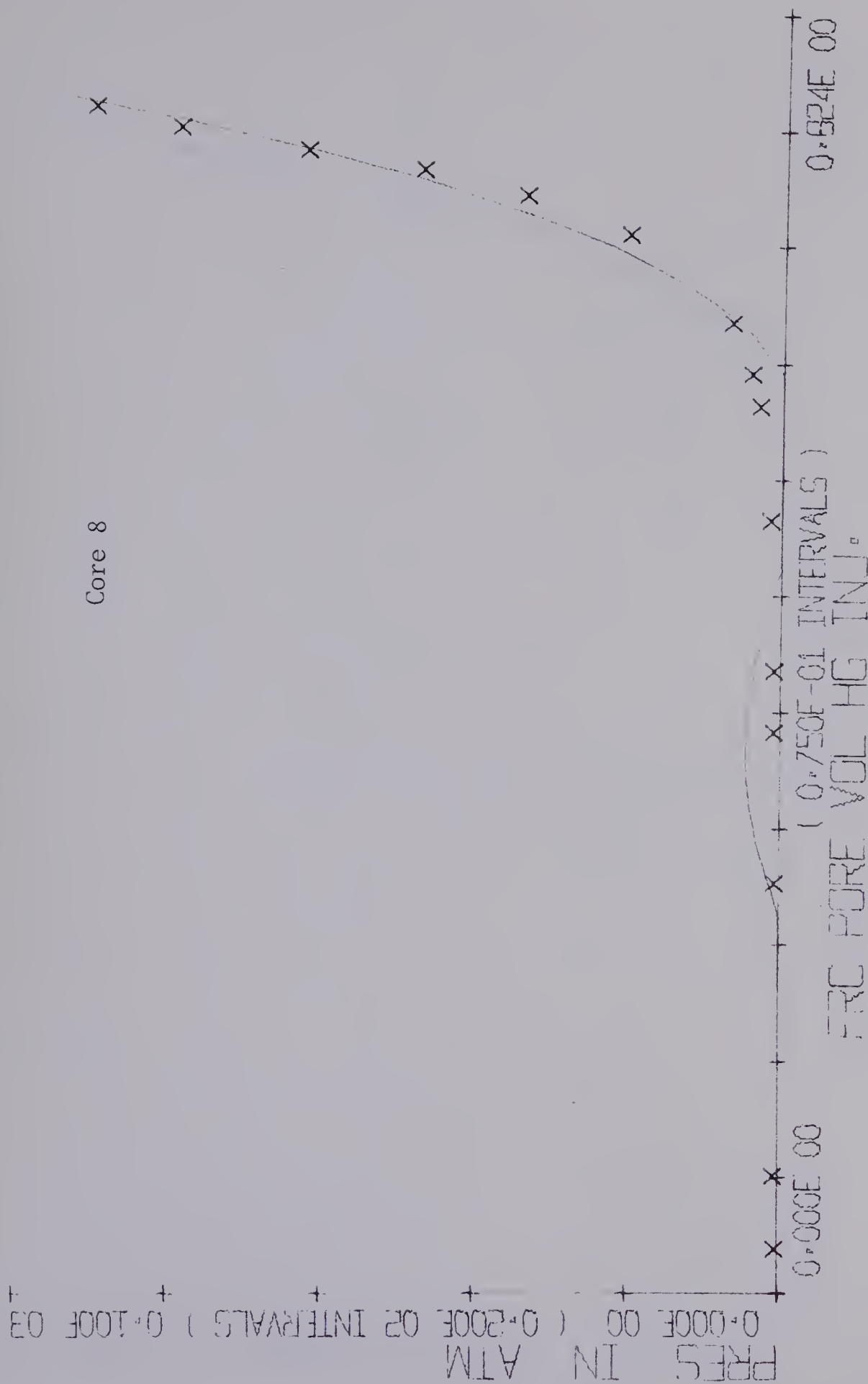


Figure IV-17. Fraction Saturation as a Function of Capillary Pressure

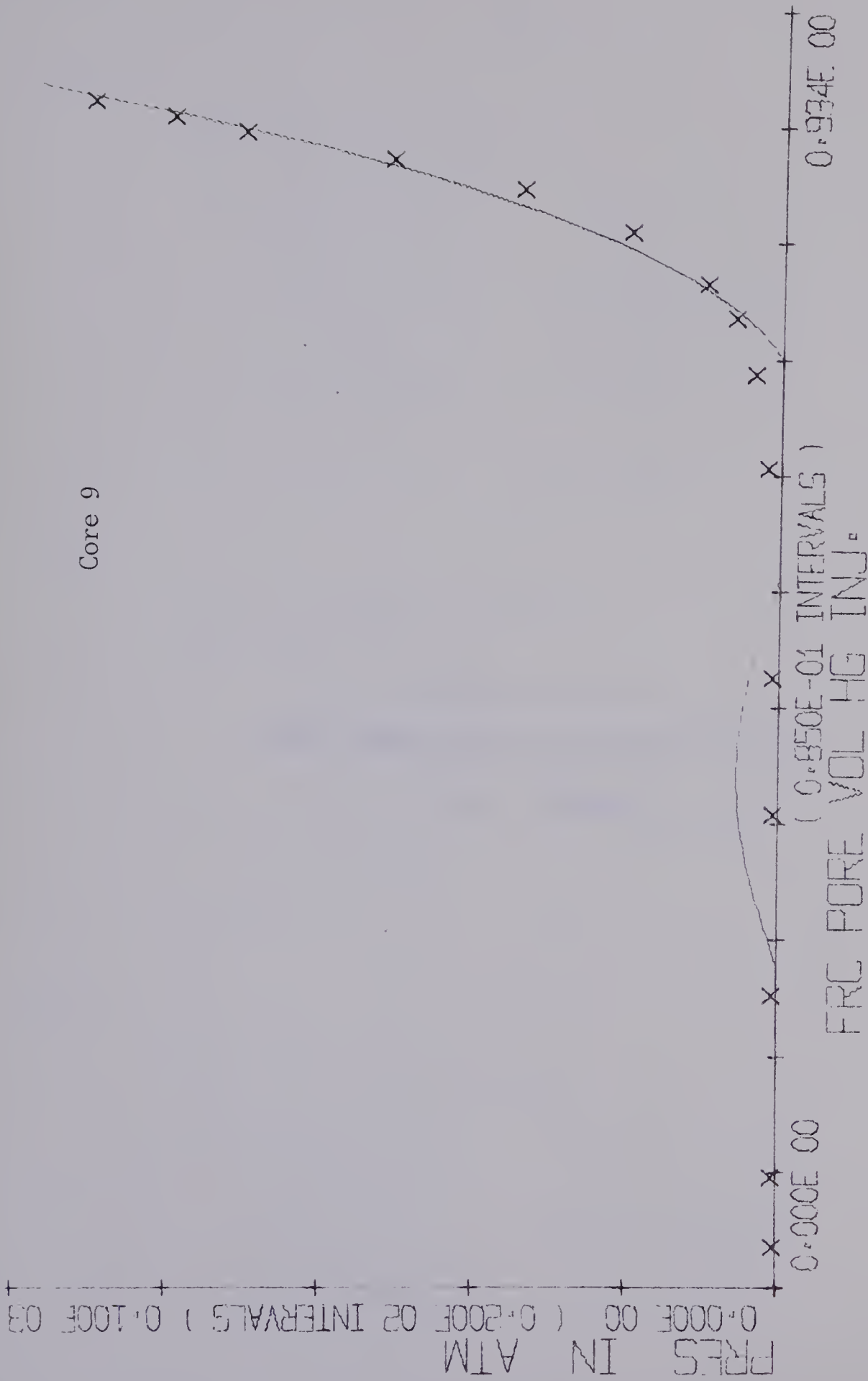


Figure IV-18. Fraction Saturation as a Function of Capillary Pressure

A P P E N D I X V
LEAST SQUARES CURVE FIT OF $1/P^2$ VS ρ FOR
CORES 1 THROUGH 9

Table V-1

Core 1

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.39687903E 01	
-0.18631174E 02	Curve Fit Variance
0.66631889E 02	
-0.14042368E 03	= 0.23169043E-02
0.10413261E 03	

Area Under the Curve = 0.89374 atm.⁻²

Core 2

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.17459298E 01	
0.98579178E 01	Curve Fit Variance
-0.54491510E 02	
0.71859282E 02	= 0.10105430E-02
-0.27408991E 02	

Area Under the Curve = 0.79929 atm.⁻²

Core 3

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.31783269E 01	
-0.69089432E 01	Curve Fit Variance
0.13318057E 02	
-0.36426334E 02	= 0.33773535E-02
0.31574387E 02	

Area Under the Curve = 0.92970 atm.⁻²

Core 4

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.36615855E 01	
-0.70324822E 01	Curve Fit Variance
0.68405607E 01	
-0.12674762E 02	= 0.19879524E-02
0.98225789E 01	

Area Under the Curve = 1.19007 atm.⁻²

Core 5

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.40148329E 01	
-0.71578119E 01	Curve Fit Variance
-0.25092969E 02	
0.68433501E 02	= 0.85084175E-03
-0.42339397E 02	

Area Under the Curve = 0.87211 atm.⁻²

Core 6

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.33371961E 01	
-0.63706977E 01	Curve Fit Variance
0.56396426E 01	
-0.14812102E 02	= 0.19648746E-02
0.14163628E 02	

Area Under the Curve = 1.00482 atm.⁻²

Core 7

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.31007128E 01

-0.68833738E 01

0.94166211E 01

-0.16703928E 02

0.11931133E 02

Curve Fit Variance

= 0.18106738E-02

Area Under the Curve = 0.95589 atm.⁻²

Core 8

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.34058828E 01

-0.51793683E 01

-0.25558236E 01

-0.23723629E 01

0.93172751E 01

Curve Fit Variance

= 0.15519927E-02

Area Under the Curve = 0.99316 atm.⁻²

Core 9

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.35043036E 01

-0.48009081E 01

0.86483380E 00

-0.86441813E 01

0.10140732E 02

Curve Fit Variance

= 0.86985066E-02

Area Under the Curve = 1.19364 atm.⁻²

A P P E N D I X V I
LEAST SQUARES CURVE FIT OF P VS ρ
FOR CORES 1 THROUGH 9

Table VI-1

Core 1

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.34566929E 02

-0.75448708E 03

0.46726082E 04

-0.10956240E 05

0.86783424E 04

Curve Fit Variance

= 0.84958572E 01

Core 2

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.17585097E 03

-0.25207883E 04

0.11725907E 05

-0.21940145E 05

0.14356480E 05

Curve Fit Variance

= 0.79437515E 01

Core 3

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.32724247E 02

-0.77455511E 03

0.45687657E 04

-0.98392184E 04

0.70613907E 04

Curve Fit Variance

= 0.13818488E 02

Core 4

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.18548316E 02

-0.38774550E 03

0.21212219E 04

-0.41281387E 04

0.26233587E 04

Curve Fit Variance

= 0.16859778E 02

Core 5

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.13564543E 02

-0.36642378E 03

0.26903001E 04

-0.69904419E 04

0.59556486E 04

Curve Fit Variance

= 0.58308239E 01

Core 6

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.10121453E 02

-0.33453549E 03

0.22467490E 04

-0.50944881E 04

0.37018154E 04

Curve Fit Variance

0.21038197E 02

Core 7

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.14336737E 02

-0.36396530E 03

0.21093671E 04

-0.42796712E 04

0.28269197E 04

Curve Fit Variance

0.22961260E 02

Core 8

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.15233667E 02

-0.45578057E 03

0.29438641E 04

-0.66679517E 04

0.49365767E 04

Curve Fit Variance

= 0.19388748E 02

Core 9

Best Fit Polynomial of Order 4

Coefficients CO to CN

0.11878129E 02

-0.32610851E 03

0.20017352E 04

-0.42015383E 04

0.28302130E 04

Curve Fit Variance

= 0.17167126E 02

A P P E N D I X V I I

RESULTS

Table VII-1

Determination of Lithology Factors Using Data
Obtained From Manually-Operated Mercury Capillary
Pressure Apparatus by Using Equation

$$K = 0.66fF \text{ Area under curve } 10^4 \text{ m d}$$

Core No.	True Permeability m d	Apparent Permeability m d	Lithology Factor
1	178.10	1843.5859	0.09660
2	155.12	1667.9025	0.09300
3	172.40	1384.9407	0.12448
4	200.50	1689.2172	0.11869
5	112.05	1006.293	0.11134

Average Lithology Factor = 0.10882

CALCULATION OF PERMEABILITIES OF CORES 6 THROUGH 9
USING PURCELL'S EQUATION AND A LITHOLOGY FACTOR OF 0.10882

Core No. 6

$$\begin{aligned} K &= 0.66 \times 0.225 \times 0.10882 \times 0.90209 \times 10^4 \text{ m d} \\ &= 145.77 \text{ m d} \end{aligned}$$

Core No. 7

$$\begin{aligned} K &= 0.66 \times 0.205 \times 0.10882 \times 0.87916 \times 10^4 \text{ m d} \\ &= 129.44 \text{ m d} \end{aligned}$$

Core No. 8

$$\begin{aligned} K &= 0.66 \times 0.263 \times 0.10882 \times 0.96029 \times 10^4 \text{ m d} \\ &= 181.39 \text{ m d} \end{aligned}$$

Core No. 9

$$\begin{aligned} K &= 0.66 \times 0.214 \times 0.10882 \times 1.075 \times 10^4 \text{ m d} \\ &= 165.22 \text{ m d} \end{aligned}$$

Table VII-2

Results From Manually-Operated
Mercury Capillary Pressure Apparatus

Core No.	True Permeability m d	Calculated Permeability m d Using Lithology Factor = 0.10882	Percent Error
6	176.80	145.77	-17.55
7	140.90	129.44	- 8.13
8	160.20	181.39	+13.22
9	177.30	165.22	- 6.81

Table VII-3

Determination of Lithology Factor Using Data
From On-Line Mercury Capillary Pressure Apparatus

Core No.	True Permeability m d	Apparent Permeability m d	Lithology* Factor
1	178.10	1887.580	0.09435
2	155.12	1545.667	0.10035
3	172.40	1564.693	0.11018
4	200.50	1892.934	0.10592
5	112.05	1179.967	0.09496

* Lithology Factor is that number that makes the observed (obtained from Klinkenberg permeameter) and calculated (obtained from capillary pressure data) permeabilities equal.

Average Lithology Factor = 0.10115

CALCULATION OF PERMEABILITIES OF CORES 6 THROUGH 9
USING PURCELL'S EQUATION AND A LITHOLOGY FACTOR OF 0.10115

Purcell's Equation

$$K = 0.66fF \times \text{Area Under Curve} \times 10^4 \text{ m d}$$

Core No. 6

$$\begin{aligned} K &= 0.66 \times 0.225 \times 0.10115 \times 1.00482 \times 10^4 \text{ m d} \\ &= 150.93 \text{ m d} \end{aligned}$$

Core No. 7

$$\begin{aligned} K &= 0.66 \times 0.205 \times 0.10115 \times 0.95589 \times 10^4 \text{ m d} \\ &= 130.82 \text{ m d} \end{aligned}$$

Core No. 8

$$\begin{aligned} K &= 0.66 \times 0.263 \times 0.10115 \times 0.99316 \times 10^4 \text{ m d} \\ &= 174.37 \text{ m d} \end{aligned}$$

Core No. 9

$$\begin{aligned} K &= 0.66 \times 0.214 \times 0.10115 \times 1.19364 \times 10^4 \text{ m d} \\ &= 170.52 \text{ m d} \end{aligned}$$

Table VII-4

Results From On-Line Mercury
Capillary Pressure Apparatus

Core No.	True Permeability m d	Calculated Permeability m d Using Lithology Factor = 0.10115	Percent Error
6	176.80	150.93	-14.63
7	140.90	130.82	- 7.15
8	160.20	174.37	+ 8.84
9	177.30	170.52	- 3.82

A P P E N D I X V I I I

SPECIFICATIONS

Pressure Transducers

Manufacturer: Consolidated Electrodynamics Corporation

Type: 4-356-0001 High Range

INPUT

Pressure Range: 0-100 psia, 0-1500 psia

Pressure Limits: 2.0 times rated pressure when applied for three (3) minutes at room temperature shall not cause a zero set to exceed 0.5% of full range output.

Rated Electrical Excitation: 10 vdc.

Maximum Electrical Excitation: 12 vdc. without damage

Input Impedance: 350 ohms nominal, 330 ohms minimum at 77°F

OUTPUT

Sensitivity: 40 mv $\pm 5\%$ open circuit, at rated excitation, and 77°F.

Residual Unbalance: within $\pm 5\%$ of full range output at zero pressure, rated excitation, and 77°F.

Linearity and Hysteresis: Combined effects of linearity and hysteresis shall not exceed $\pm 0.25\%$ of full range output as measured from the best straight line through the calibration points.

Natural Frequency: Approximately 30,000 Hz for 100 psi transducers increasing logarithmically with pressure range to 56,000 Hz for 5000 psi transducers.

Output Impedance: 350 ohms $\pm 10\%$ at 77°F

Resolution: Infinite

ENVIRONMENTAL

Compensated Temperature Range: -65°F to $+250^{\circ}\text{F}$

Operable Temperature Range: -320°F to $+300^{\circ}\text{F}$

Thermal Zero Shift: Within 0.01% FR/ $^{\circ}\text{F}$ over the compensated temperature range.

Thermal Sensitivity Shift: Within 0.005% FR/ $^{\circ}\text{F}$ over the compensated temperature range.

Static Acceleration: At 100g the response shall not exceed 0.005% FR/g for 100 psi transducers decreasing logarithmically with pressure range to 0.003% FR/g for 5000 psi transducers.

Linear Vibration: At 35g peak sinusoidal vibration from 5 to 2000 Hz (limited by 1/2-inch D.A.) the response shall not exceed 0.03% FR/g for 100 psi transducers decreasing logarithmically with pressure range to 0.02% FR/g for 1000 psi transducers and above.

Altitude: Ambient pressure from 0 to 60 psia shall not affect the transducers.

Shock: 1000g half sine wave pulse for a duration of one millisecond shall not damage the transducers.

PHYSICAL

Pressure Connection: 1/4-inch male flare tube fitting per MS33656-4

Pressure Cavity Volume: 0.023 cu.in.

Insulation Resistance: 500 megohms minimum at 45 vdc over the compensated temperature range.

Weight: 2.5 ounces maximum, excluding mating connector.

Type: 4-356-0002 Low Range

All specifications identical to those for 4-356-0001,
except the following:

INPUT

Pressure Range: 0-50 psia

OUTPUT

Natural Frequency: 26,000 Hz for 99 psi transducer decreasing
logarithmically with pressure range to 16,000 Hz for 25
psi transducer and below.

ENVIRONMENTAL

Static Acceleration: At 100 g the response shall not exceed
0.035% FR/g for 10 psi transducers decreasing logarith-
mically with pressure range to 0.03% FR/g for 99 psi
transducers.

Altitude: Ambient pressure from 0 psia to 2 times rated
range shall not damage absolute transducers.

Ambient Pressure: From 1-60 psia shall not damage gauge
transducers.

Linear Displacement Transducer

Manufacturer: Hewlett Packard

Model: 24DCDT-3000

Transducer Type: DC-input, DC-output differential transformer
with built-in carrier oscillator and phase-sensitive de-
modulator providing DC output proportional to linear
displacement

Input: Displacements to $\pm 3.0''$ full scale.

Output: DC voltage amplitude proportional to core (armature) displacement and polarity related to the direction of displacement. Deviation from the best straight line through zero not more than 0.5% of total stroke range.

Sensitivity: Full scale output to ± 13.0 vdc, requiring 24 vdc nominal excitation.

Size and weight: 0.75" diameter x 10.52" long and 208 grams.

Temperature Range: -65°F to 250°F

Output Impedance: 5.6 K-ohms.

Power Supplies

1. For Pressure Transducers

Manufacturer: Hewlett Packard

Model: 801C

Specifications:

Output: 0 to 25 vdc at 0 to 0.2 amp.

Load Regulation: less than 2 mv change, no load to full load.

Line Regulation: Less than 2 mv change, for a change in line voltage from 105 to 125 volts.

Ripple and Noise: less than $100\mu\text{v}$ rms.

Maximum Ambient Operating Temperature: 50°C

Stability: Less than 0.1% + 5 mv, total drift for 8 hours after 30 minutes warm up.

Overload Protection: Current limiter protects supply from all overloads including direct shorts.

Controls: Coarse and vernier for continuous voltage control.

Power: 105 to 125 vac, 55-65 Hz.

Dimensions: 5" high, 14-7/8" deep, 1-5/8" wide.

Weight: 4 lbs.

2. For Linear Displacement Transducer

Manufacturer: Hewlett Packard

Model: 6204B

Input: 115 v ac $\pm 10\%$, 50-400 Hz, 0.4 A, 24 W

Output: 0-20V 0-40V
 0-0.6A 0-0.3A

Load Regulation: Constant voltage, 0.01% plus 4 mv

Line Regulation: Constant voltage, 0.01% plus 4 mv

Ripple and Noise: Constant voltage, 200 μ V rms

Overload Protection: Fixed current limit provides complete protection for every overload condition. This limit is set at approximately 700 ma for the 20 volts range and 350 ma for the 40 volt range.

Weight: 10-13 lbs.

A P P E N D I X I X

DATA CORRECTED FOR CELL EXPANSION AND
MERCURY COMPRESSION DUE TO PRESSURE

Table IX-1

Mercury Capillary Pressure Data Corrected for
Cell Expansion and Mercury Contraction Due to Pressure

Core 1

Bulk Volume = 13.26 c c

Porosity = 0.320

Pore Volume = 4.243 c c

Cum. Vol. Hg Injected, After Cell & Mercury Correction	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.232	0.5766	0.0546	3.00776
0.812	0.7343	0.19136	1.85431
1.102	0.8018	0.2597	1.55521
1.363	0.8881	0.3212	1.26787
1.497	0.9175	0.3527	1.18788
1.974	0.9590	0.4652	0.26056
2.156	3.9399	0.5081	0.06441
2.201	4.9678	0.5187	0.04051
2.237	5.9209	0.5272	0.02852
2.324	10.7881	0.5476	0.00859
2.411	18.2762	0.5682	0.00299
2.451	25.5601	0.5776	0.00153
2.504	37.3368	0.5901	0.00071
2.539	54.2190	0.5983	0.00034
2.566	71.0332	0.6047	0.00019

Table IX-2

Mercury Capillary Pressure Data Corrected for
Cell Expansion and Mercury Contraction Due to Pressure

Core 2

Bulk Volume = 13.250 c c

Porosity = 0.293

Pore Volume = 3.882 c c

Cum. Vol. Hg Injected, After Cell & Mercury Correction	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.453	0.62005	0.1166	2.60100
1.015	0.76209	0.2614	1.72177
1.278	0.85066	0.3291	1.38190
1.7279	1.32595	0.4450	0.56877
1.988	2.89164	0.5120	0.11959
2.0879	4.18504	0.5378	0.05709
2.2180	7.62275	0.5713	0.01720
2.3379	17.25516	0.6022	0.00335
2.4059	29.50839	0.6197	0.00114
2.4359	39.71943	0.6274	0.00063
2.4559	51.29193	0.6326	0.00038
2.4709	64.22591	0.6364	0.00024
2.4809	75.79841	0.6390	0.00017
2.5039	83.96722	0.6449	0.00014
2.49899	89.41310	0.6436	0.00012

Table IX-3

Mercury Capillary Pressure Data Corrected for
Cell Expansion and Mercury Contraction Due to Pressure

Core 3

Bulk Volume = 13.697 c c

Porosity = 0.255

Pore Volume = 3.492 c c

Cum. Vol. Hg Injected, After Cell & Mercury Correction	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.14100	0.59458	0.0403	2.8286
0.74300	0.72827	0.2127	1.88542
1.15400	0.85294	0.3304	1.37455
1.32900	0.92881	0.3805	1.15916
1.6839	1.67761	0.4821	0.35531
1.85399	2.97442	0.53081	0.11303
1.94400	4.16230	0.5565	0.05772
2.05400	7.70212	0.5880	0.01685
2.13899	14.74773	0.6124	0.00459
2.23899	30.74502	0.6410	0.00105
2.26199	43.33862	0.6476	0.00053
2.28899	58.58709	0.6553	0.00029
2.31299	72.61025	0.6622	0.00018
2.31799	84.31889	0.66366	0.00014
2.32799	93.50882	0.66652	0.00011

Table IX-4

Mercury Capillary Pressure Data Corrected for
Cell Expansion and Mercury Contraction Due to Pressure

Core 4

Bulk Volume = 13.33 c c

Porosity = 0.241

Pore Volume = 3.212 c c

Cum. Vol. Hg Injected, After Cell & Mercury Correction	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.122	0.52606	0.03797	3.61338
0.412	0.62466	0.1282	2.56274
1.170	0.82185	0.3641	1.48049
1.434	0.92881	0.4463	1.15916
1.821	1.57550	0.5668	0.40286
2.031	2.86890	0.6322	0.12149
2.126	4.33248	0.6617	0.05327
2.231	7.34133	0.6944	0.01855
2.371	16.82398	0.7380	0.00353
2.468	31.57751	0.7682	0.00100
2.509	44.50948	0.7810	0.00050
2.530	57.51153	0.7875	0.00030
2.5569	71.73889	0.7959	0.00019
2.5749	84.65926	0.8015	0.00013
2.5979	95.57143	0.8086	0.00010

Table IX-5

Mercury Capillary Pressure Data Corrected for
Cell Expansion and Mercury Contraction Due to Pressure

Core 5

Bulk Volume = 13.319 c c

Porosity = 0.205

Pore Volume = 2.730 c c

Cum. Vol. Hg Injected, After Cell & Mercury Correction	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.068	0.5264	0.0249	3.60879
0.286	0.61998	0.1047	2.60156
0.392	0.66677	0.1435	2.24924
0.624	0.81383	0.2285	1.50982
0.962	1.43121	0.3523	0.48819
1.182	2.96967	0.4328	0.11339
1.2519	4.20861	0.4584	0.05645
1.3609	7.40807	0.4983	0.01822
1.469	17.40127	0.5379	0.00330
1.5019	28.02073	0.5500	0.00127
1.5599	44.49454	0.5712	0.00050
1.5749	58.65382	0.5767	0.00029
1.5960	71.58781	0.5844	0.00019
1.6119	81.52654	0.5903	0.00015
1.6189	92.69060	0.5928	0.00011

Table IX-6

Mercury Capillary Pressure Data Corrected for
Cell Expansion and Mercury Contraction Due to Pressure

Core 6

Bulk Volume = 13.46 c c

Porosity = 0.225

Pore Volume = 3.028 c c

Cum. Vol. Hg Injected, After Cell & Mercury Correction	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.026	0.56383	0.00858	3.14552
0.402	0.63435	0.1327	2.48502
0.743	0.75768	0.2453	1.74188
1.056	0.87967	0.3486	1.29226
1.192	0.92312	0.3935	1.17348
1.5579	1.65151	0.5144	0.36663
1.7379	3.0334	0.5738	0.10867
1.8079	4.22469	0.5969	0.05602
1.8979	6.91359	0.6266	0.02092
2.0379	19.09876	0.6729	0.00274
2.089	30.87548	0.6897	0.00104
2.1079	44.49019	0.6960	0.00050
2.0829	58.78563	0.6877	0.00028
2.1499	72.38671	0.7098	0.00019
2.1599	90.91633	0.7131	0.00012

Table IX-7

Mercury Capillary Pressure Data Corrected to
Cell Expansion and Mercury Contraction Due to Pressure

Core 7

Bulk Volume = 13.159 c c

Porosity = 0.205

Pore Volume = 2.697 c c

Cum. Vol. Hg Injected, After Cell & Mercury Correction	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.034	0.57987	0.0126	2.97388
0.259	0.62934	0.0960	2.52477
0.708	0.81985	0.2624	1.48774
0.960	0.92012	0.3558	1.18116
1.070	0.93014	0.3966	1.15583
1.4969	1.81510	0.5548	0.30352
1.6359	2.97235	0.6064	0.11318
1.7039	4.26573	0.6316	0.05495
1.8109	7.73750	0.67127	0.01670
1.936	17.94853	0.7176	0.00310
2.00599	32.78856	0.7435	0.00093
2.0139	46.40327	0.7465	0.00046
2.0439	62.87706	0.7576	0.00025
2.2609	79.75930	0.8380	0.00015
2.0679	92.28483	0.7665	0.00011

Table IX-8

Mercury Capillary Pressure Data Corrected to
Cell Expansion and Mercury Contraction Due to Pressure

Core 8

Bulk Volume = 13.20 c c

Porosity = 0.263

Pore Volume = 3.471 c c

Cum. Vol. Hg Injected, After Cell & Mercury Correction	Pressure atm	Frc.Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.036	0.56885	0.0103	3.09032
0.202	0.59024	0.05818	2.87039
0.872	0.74899	0.2511	1.78254
1.1819	0.89939	0.3404	1.23622
1.310	0.92112	0.3773	1.17859
1.6579	1.4623	0.4775	0.46765
1.8869	2.96469	0.5435	0.11377
1.9599	4.05522	0.5645	0.06080
2.0579	6.7768	0.5927	0.02177
2.2199	20.7985	0.6394	0.00231
2.2769	34.4133	0.6558	0.00084
2.3099	47.7557	0.6653	0.00043
2.3209	62.8680	0.6685	0.00025
2.3309	79.2056	0.6714	0.00015
2.3529	90.5058	0.6777	0.00012

Table IX-9

Mercury Capillary Pressure Data Corrected to
Cell Expansion and Mercury Contraction Due to Pressure

Core 9

Bulk Volume = 13.30 c c

Porosity = 0.214

Pore Volume = 2.846 c c

Cum. Vol. Hg Injected, After Cell & Mercury Correction	Pressure atm	Frc. Pore Vol. Filled With Hg	1/Pres. ² atm ⁻²
0.027	0.53041	0.009486	3.5544
0.175	0.58021	0.06148	2.97046
0.560	0.64070	0.1967	2.43601
0.926	0.70955	0.3253	1.9862
1.183	0.92346	0.4156	1.17263
1.5979	1.77438	0.5614	0.31761
1.7779	3.44218	0.6246	0.08439
1.8979	6.09705	0.6668	0.0269
1.9829	9.92959	0.6966	0.01014
2.0709	19.98405	0.7276	0.00250
2.1309	34.55178	0.7486	0.00083
2.1560	51.63824	0.7575	0.00037
2.1879	70.63078	0.7687	0.00020
2.202	80.02491	0.7736	0.00015
2.212	90.37209	0.7771	0.00012

CALCULATION OF PERMEABILITIES OF
CORES 1 THROUGH 5

Core 1

$$\begin{aligned} K &= 0.66 \times 0.32 \times 0.82988 \times 10^4 \text{ m d} \\ &= 1752.70 \text{ m d} \end{aligned}$$

Core 2

$$\begin{aligned} K &= 0.66 \times 0.293 \times 0.8295 \times 10^4 \text{ m d} \\ &= 1604.087 \text{ m d} \end{aligned}$$

Core 3

$$\begin{aligned} K &= 0.66 \times 0.255 \times 0.8013 \times 10^4 \text{ m d} \\ &= 1348.58 \text{ m d} \end{aligned}$$

Core 4

$$\begin{aligned} K &= 0.66 \times 0.241 \times 1.0236 \times 10^4 \text{ m d} \\ &= 1623.13 \text{ m d} \end{aligned}$$

Core 5

$$\begin{aligned} K &= 0.66 \times 0.205 \times 0.70931 \times 10^4 \text{ m d} \\ &= 959.69 \text{ m d} \end{aligned}$$

Table IX-10

Determination of Lithology Factors Using Data
Obtained From Manually-Operated Mercury Capillary Pressure
Apparatus After Correcting for Cell Expansion and
Mercury Contraction Due to Pressure

Core No.	True Permeability m d	Apparent Permeability m d	Lithology Factor
1	178.10	1752.70	0.10161
2	155.12	1604.08	0.09670
3	172.40	1348.58	0.12783
4	200.50	1623.13	0.12352
5	112.05	959.69	0.11675

Average Lithology Factor = 0.11328

CALCULATION OF PERMEABILITIES OF CORES 6 THROUGH 9
USING PURCELL'S EQUATION AND A LITHOLOGY FACTOR OF 0.11328

Core No. 6

$$\begin{aligned} K &= 0.66 \times 0.225 \times 0.8740 \times 0.11328 \times 10^4 \text{ m d} \\ &= 147.02 \text{ m d} \end{aligned}$$

Core No. 7

$$\begin{aligned} K &= 0.66 \times 0.205 \times 0.8464 \times 0.11328 \times 10^4 \text{ m d} \\ &= 129.72 \text{ m d} \end{aligned}$$

Core No. 8

$$\begin{aligned} K &= 0.66 \times 0.263 \times 0.92771 \times 0.11328 \times 10^4 \text{ m d} \\ &= 182.41 \text{ m d} \end{aligned}$$

Core No. 9

$$\begin{aligned} K &= 0.66 \times 0.214 \times 1.0436 \times 0.11328 \times 10^4 \text{ m d} \\ &= 166.973 \text{ m d} \end{aligned}$$

Table IX-11

Effect of Neglecting Cell Expansion and
Mercury Contraction Due to Pressure

Core No.	Calculated Permeability m d (With Correction)	Calculated Permeability m d (Without Correction)	Percent Error Introduced
6	147.02	145.77	-0.85
7	129.72	129.44	-0.215
8	182.41	181.39	-0.559
9	166.973	165.22	-1.049

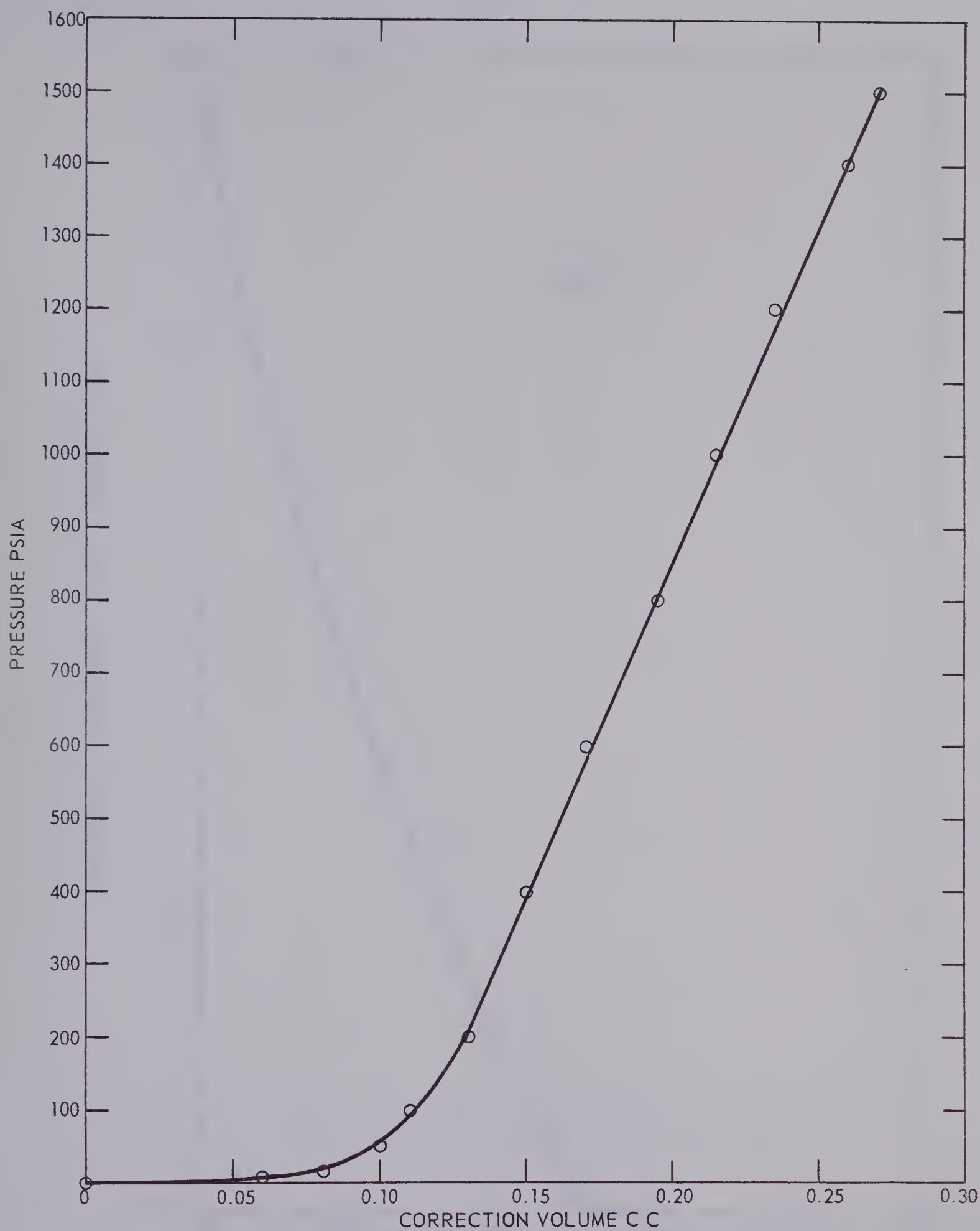


Figure IX-1. CORRECTION CURVE FOR MERCURY CELL DUE TO CELL EXPANSION AND
MERCURY CONTRACTION WITH PRESSURE

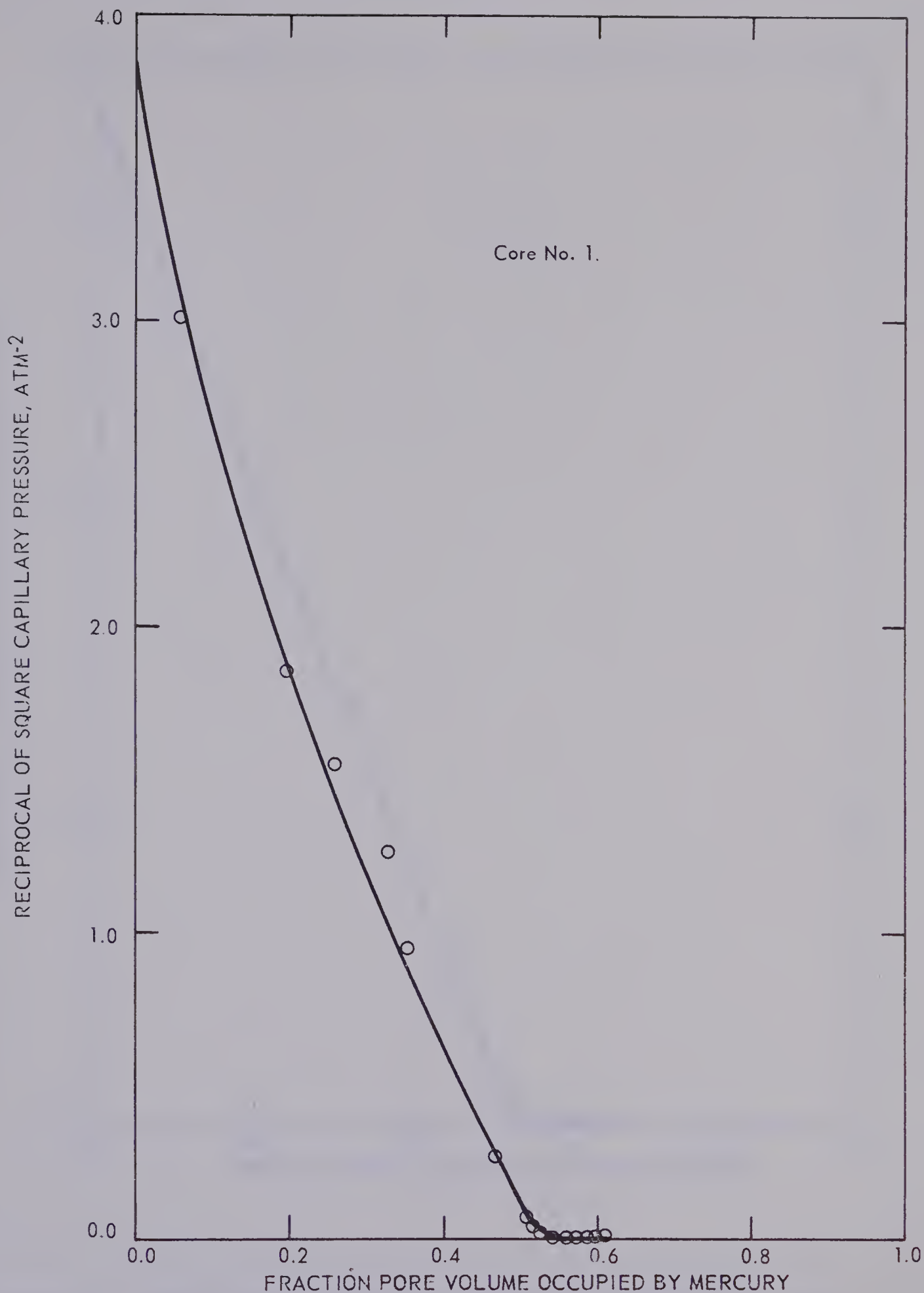


Figure IX-2 FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE.

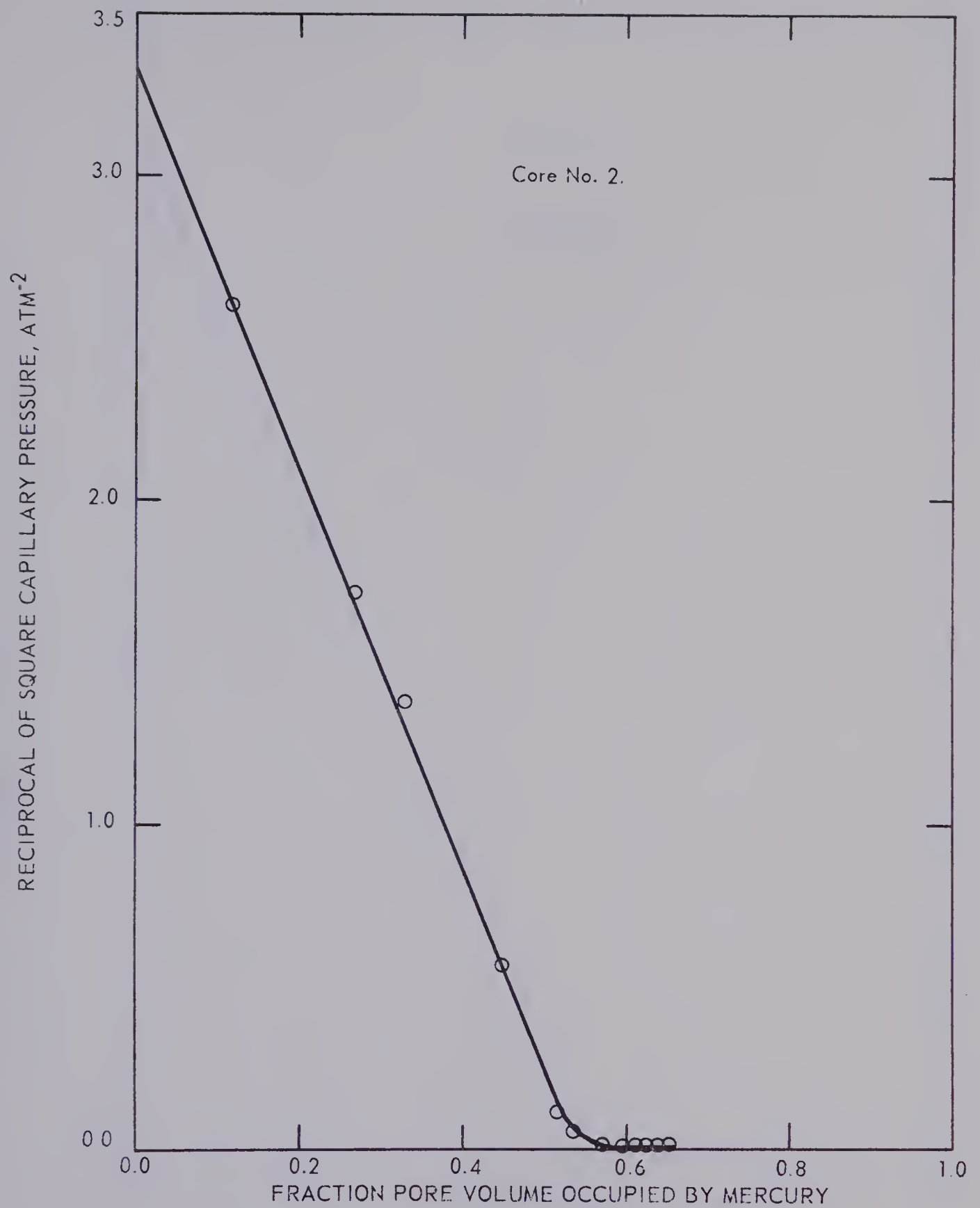


Figure IX-3. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE

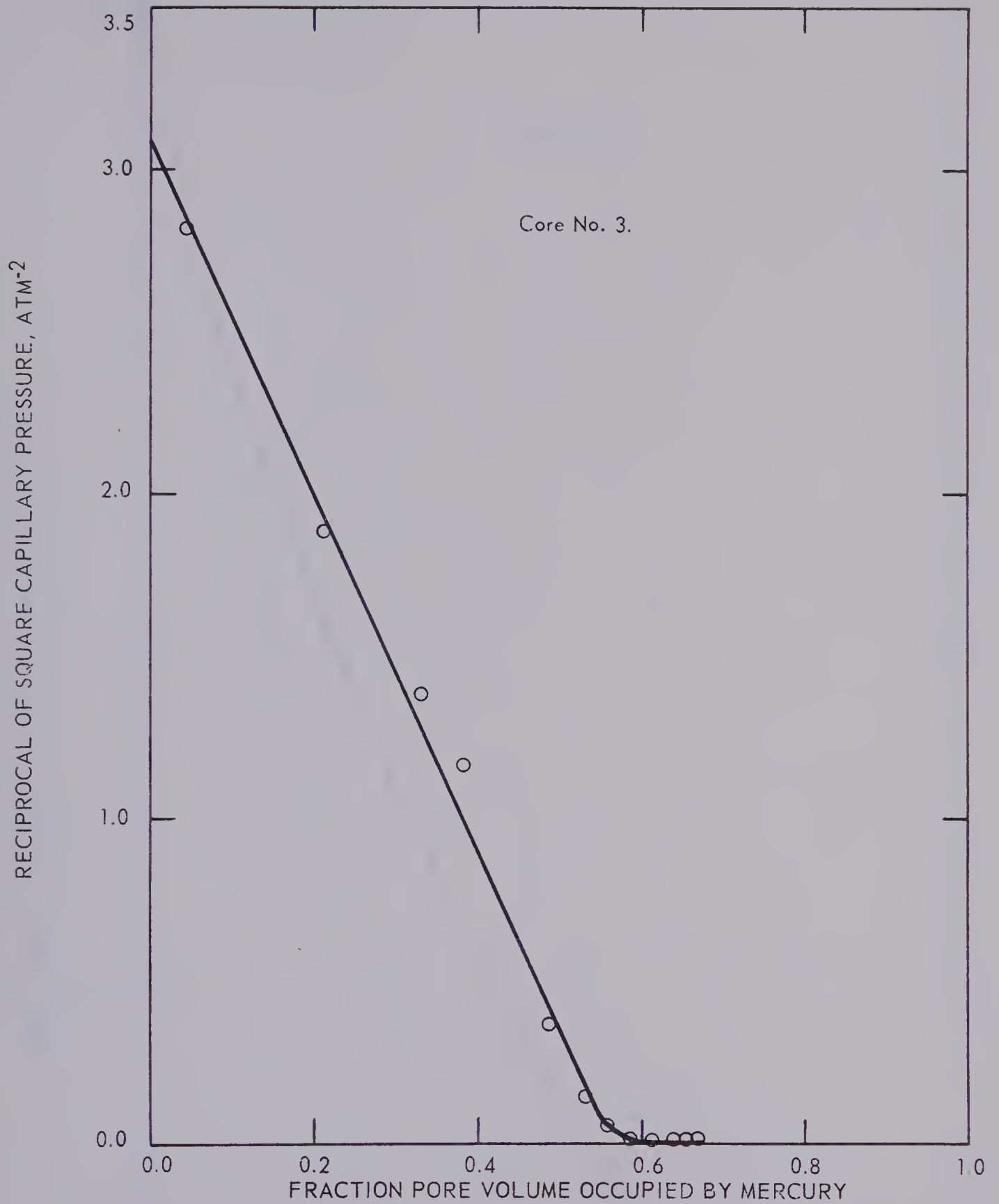


Figure IX-4 FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF
SQUARE CAPILLARY PRESSURE

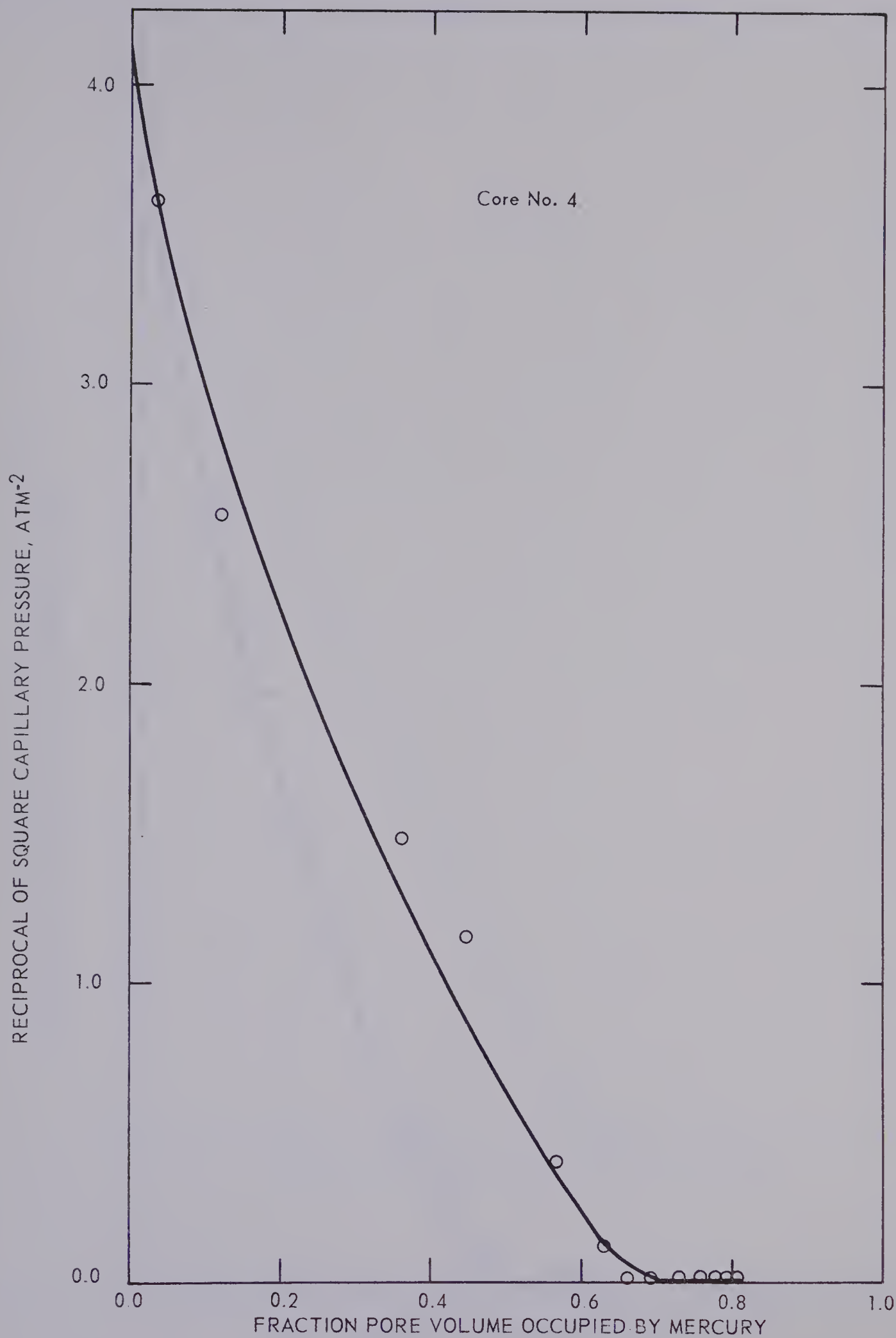


Figure IX-5 FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE

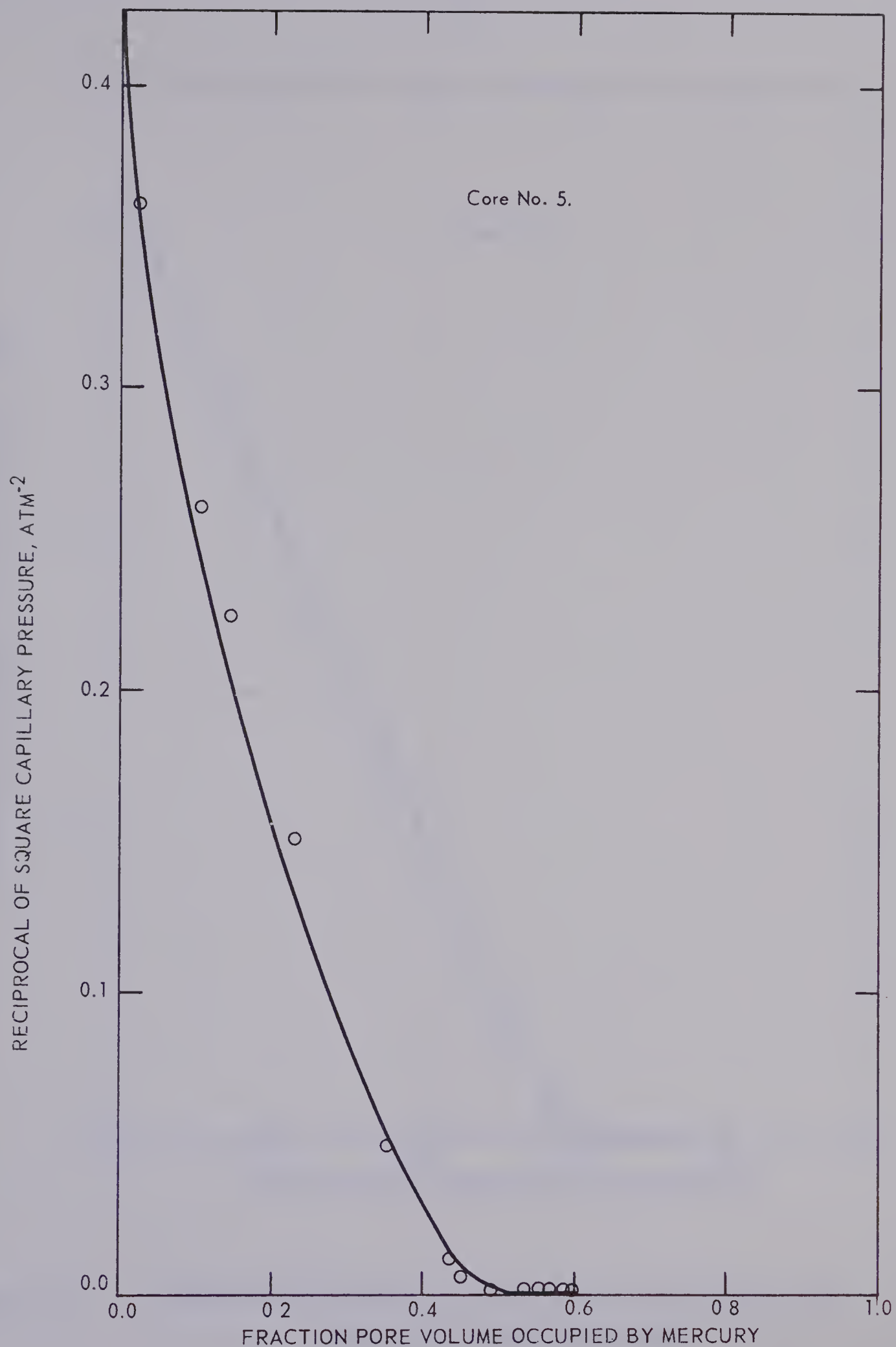


Figure IX-6. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE

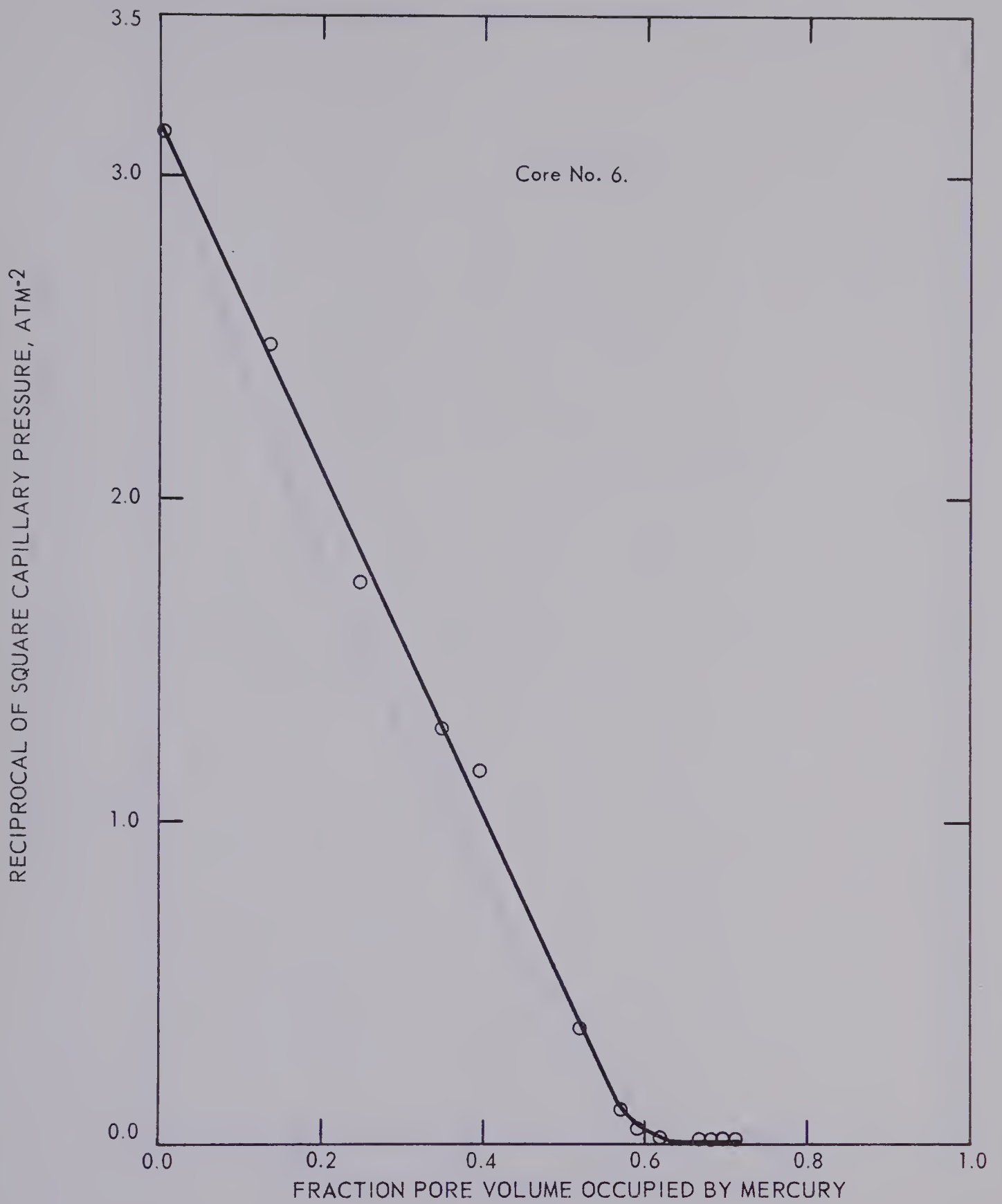


Figure IX-7

FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF
SQUARE CAPILLARY PRESSURE

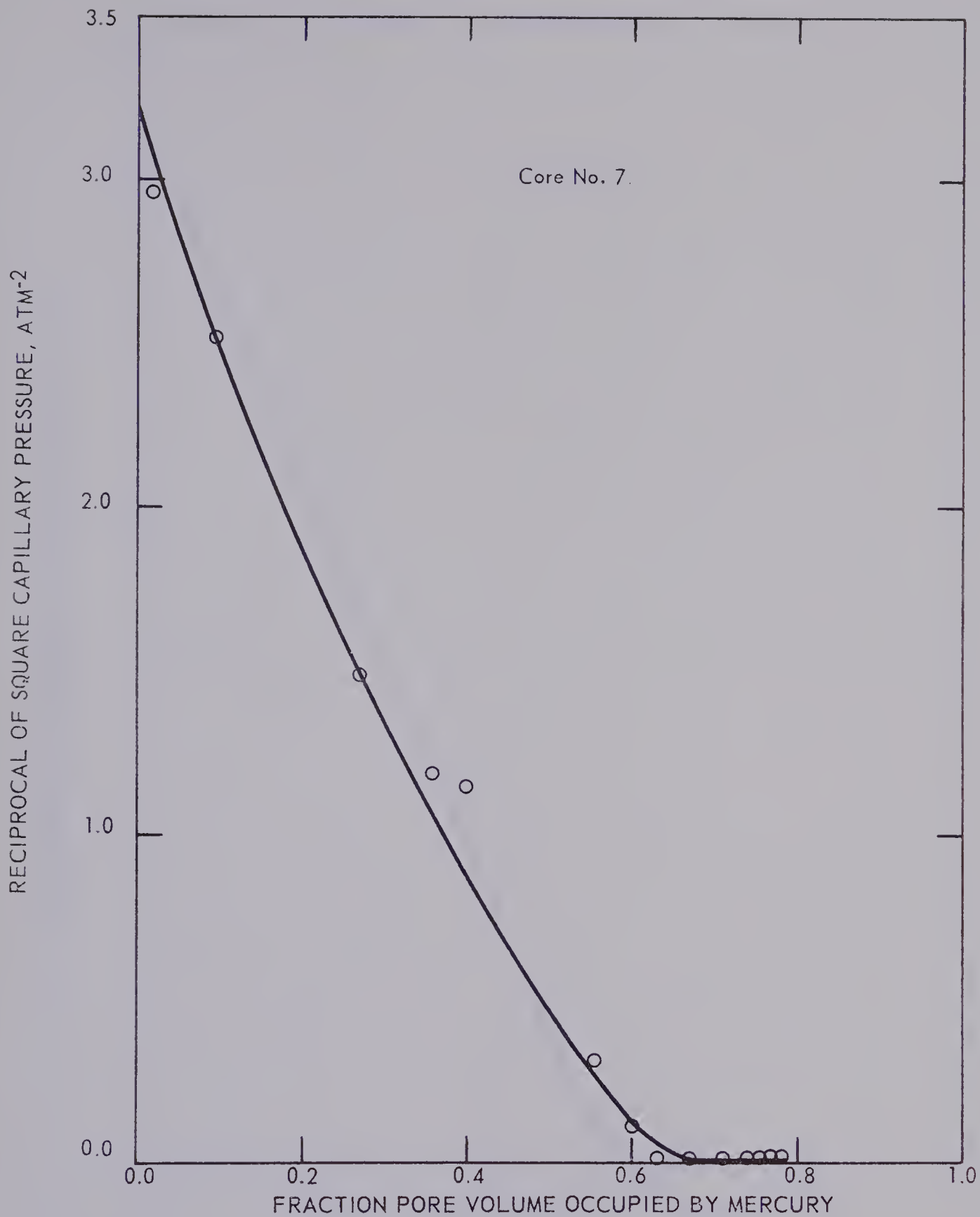


Figure IX-8. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE.

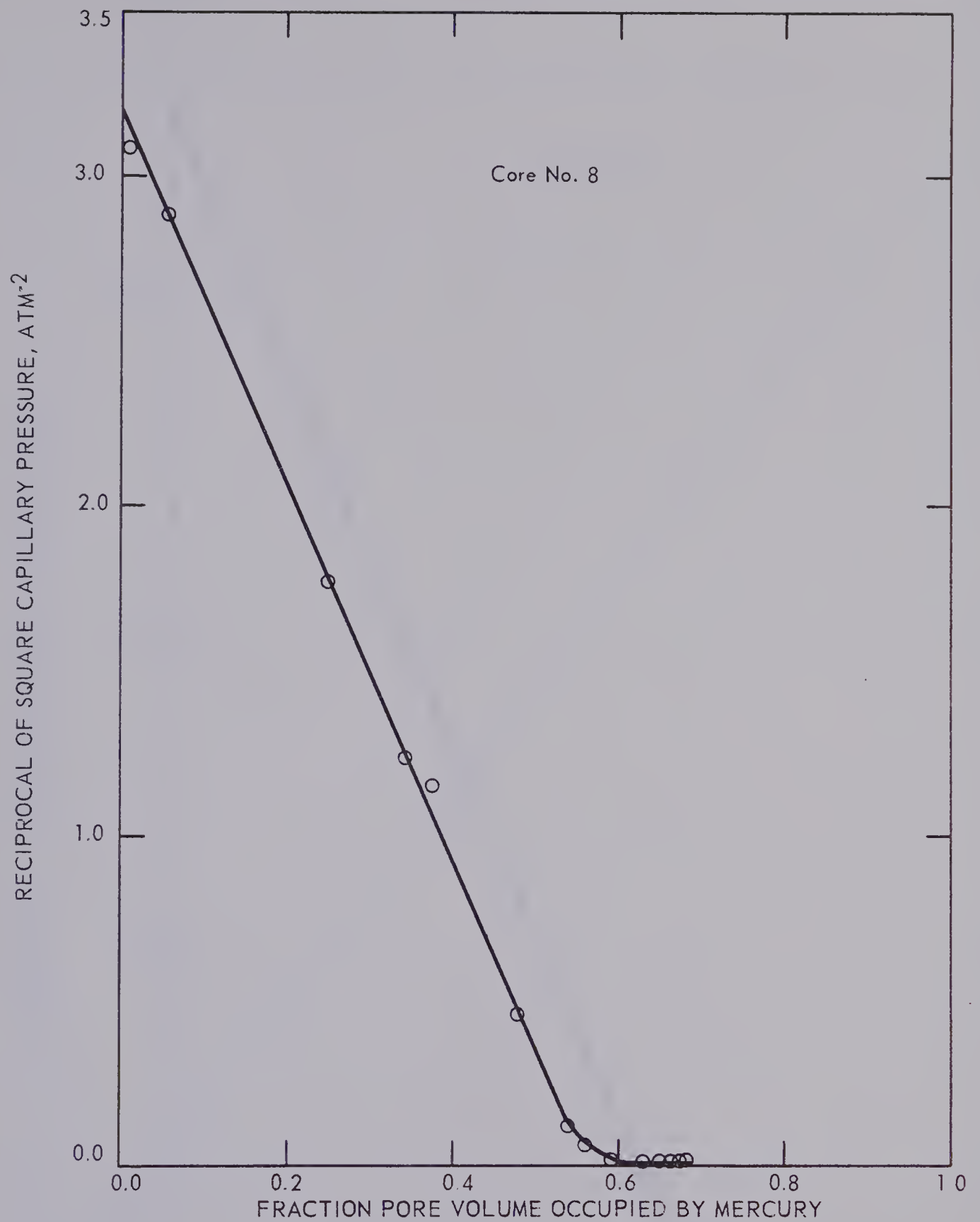


Figure IX-9. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE

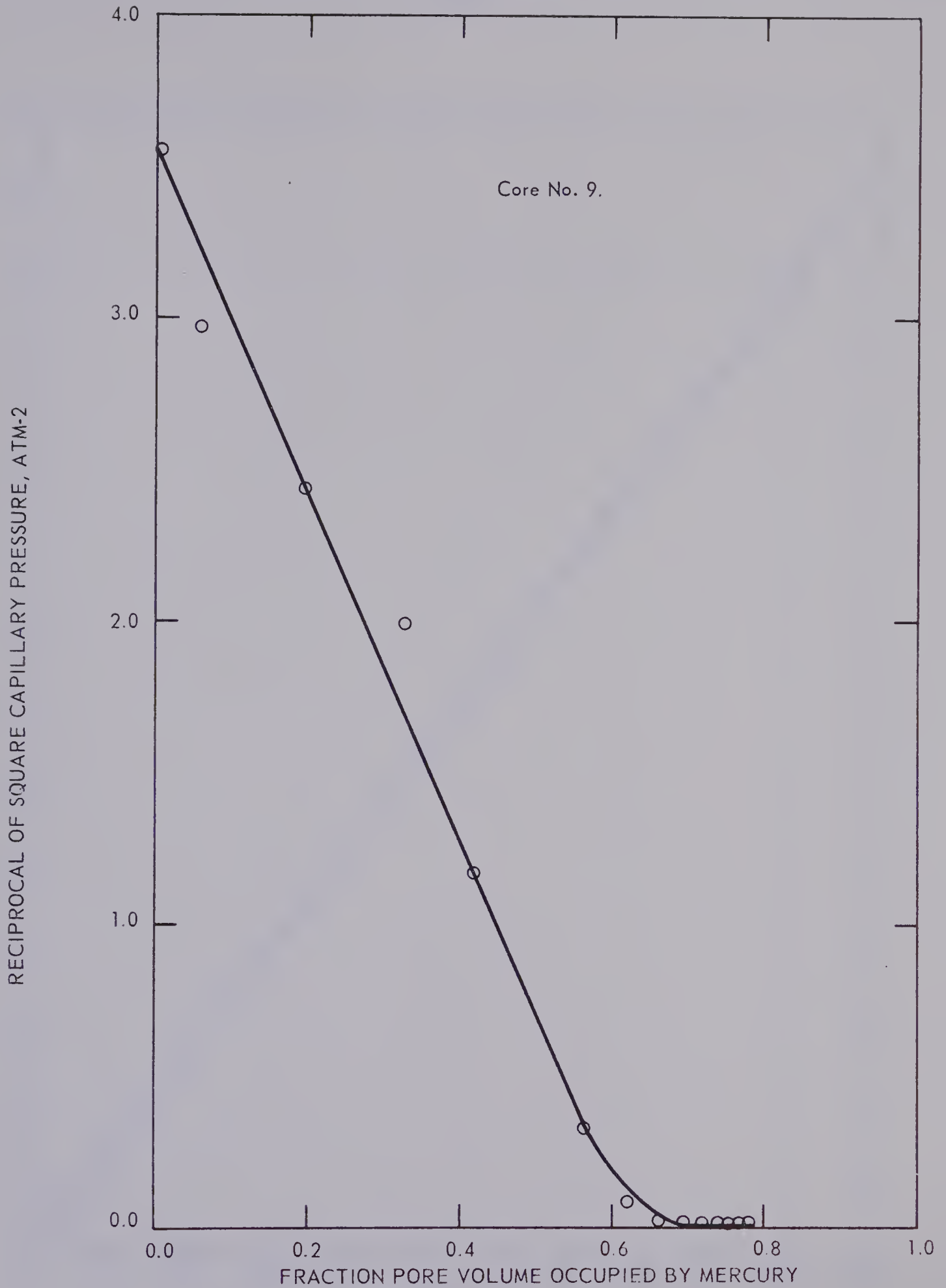


Figure IX-10. FRACTION SATURATION AS A FUNCTION OF RECIPROCAL OF SQUARE CAPILLARY PRESSURE.

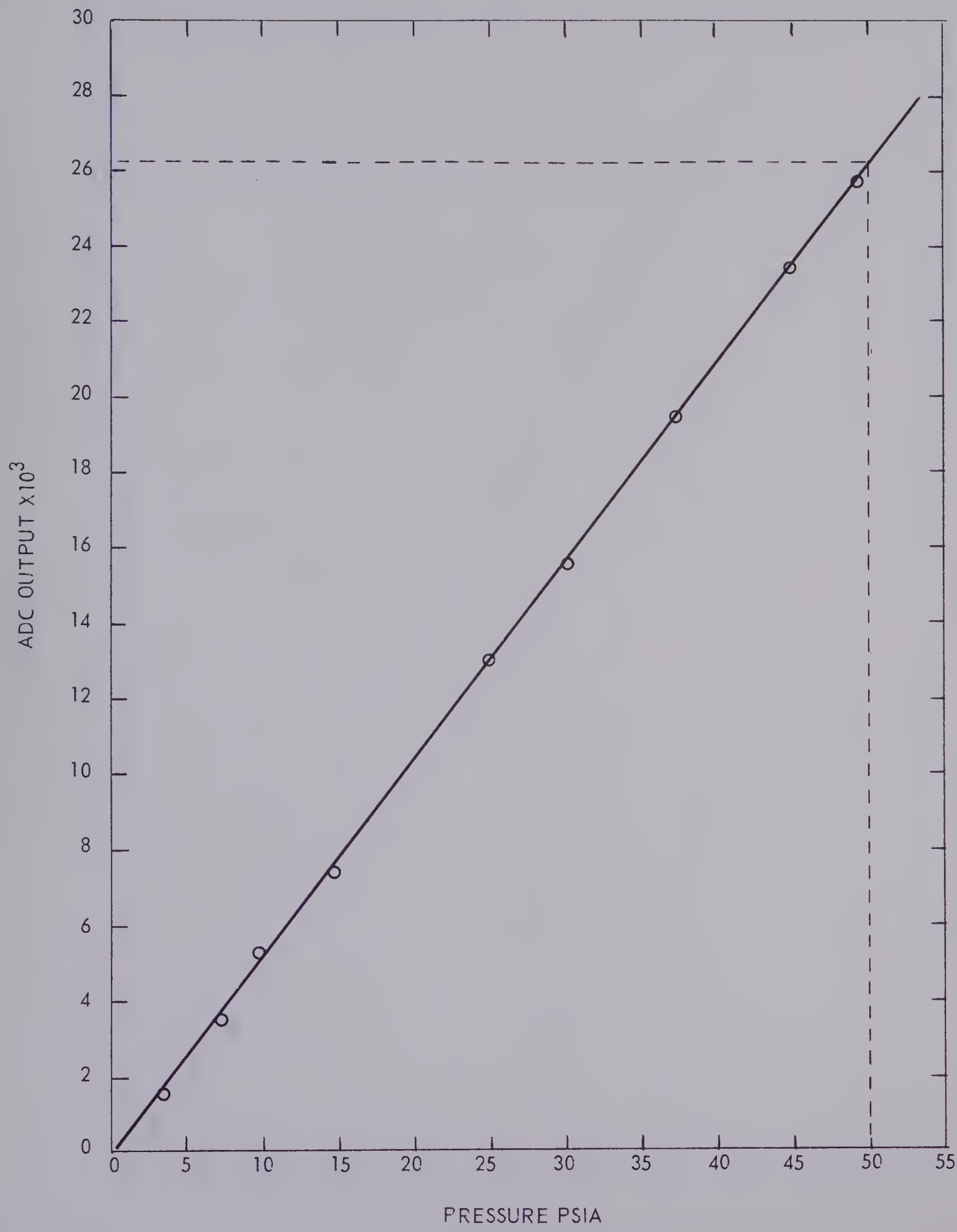


Figure 1X-11 CALIBRATION CURVE FOR PRESSURE TRANSDUCER
0-50 PSIA

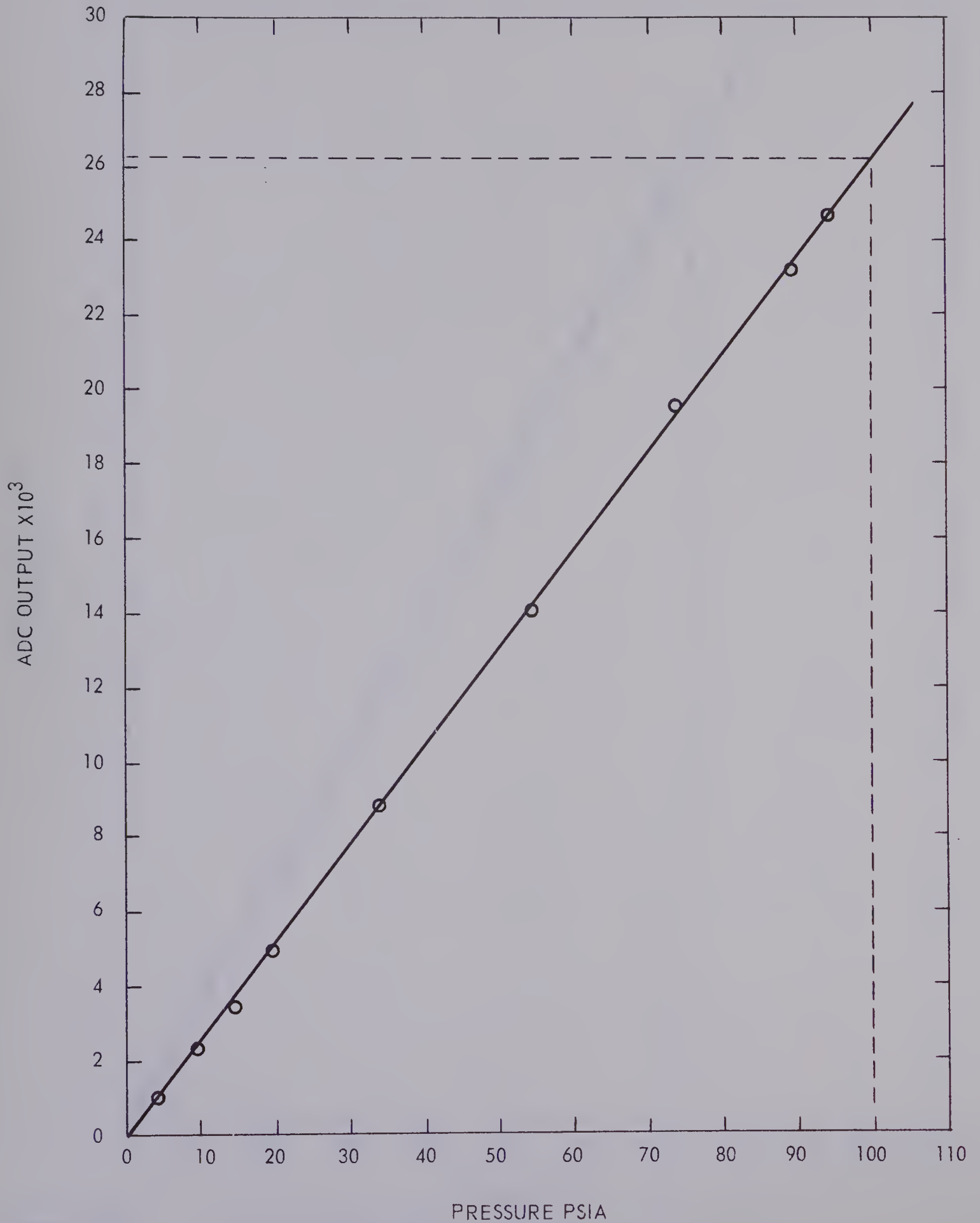


Figure 1X-12

CALIBRATION CURVE FOR PRESSURE TRANSDUCER
0-100 PSIA

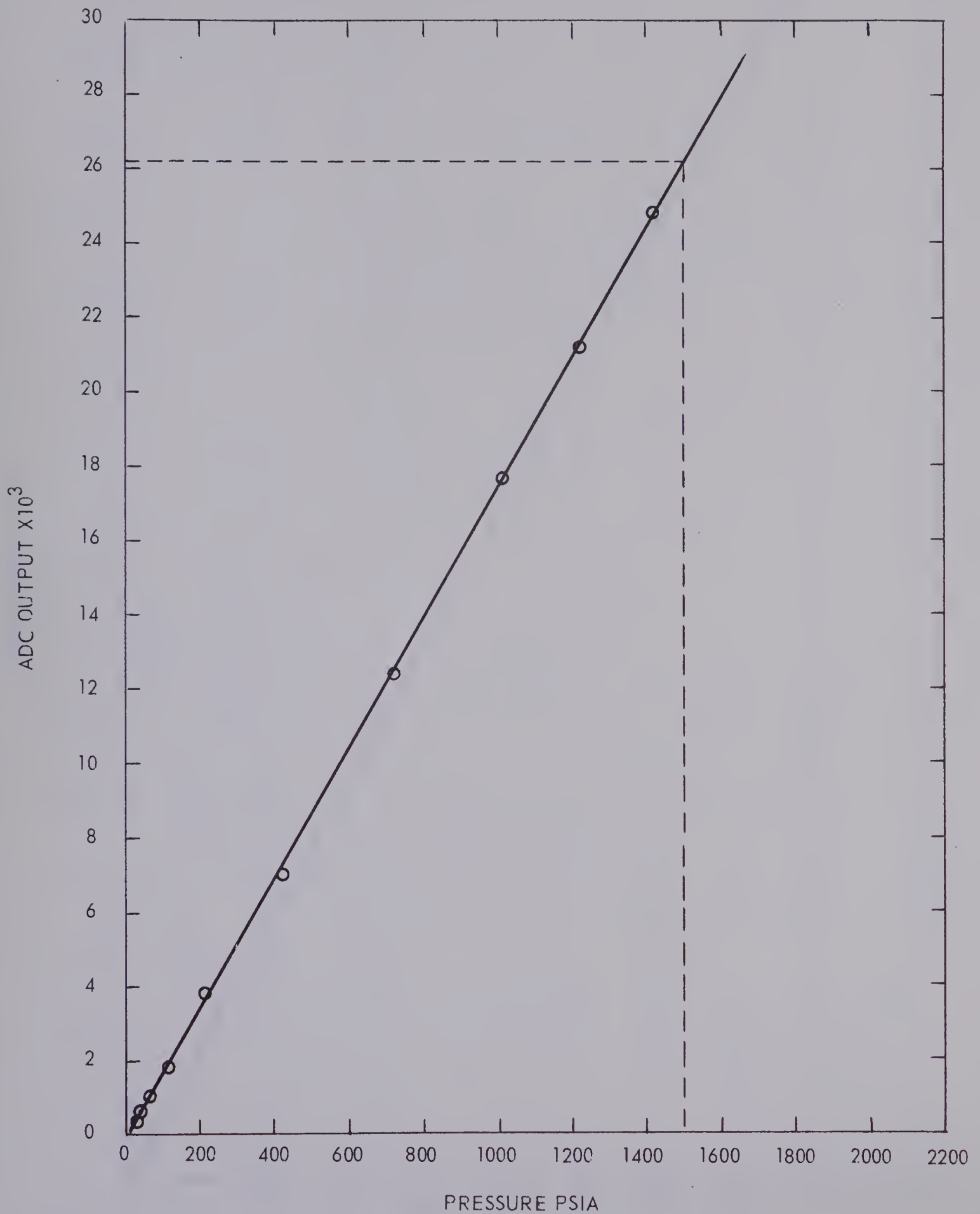


Figure 1X-13

CALIBRATION CURVE FOR PRESSURE TRANSDUCER
0-1500 PSIA

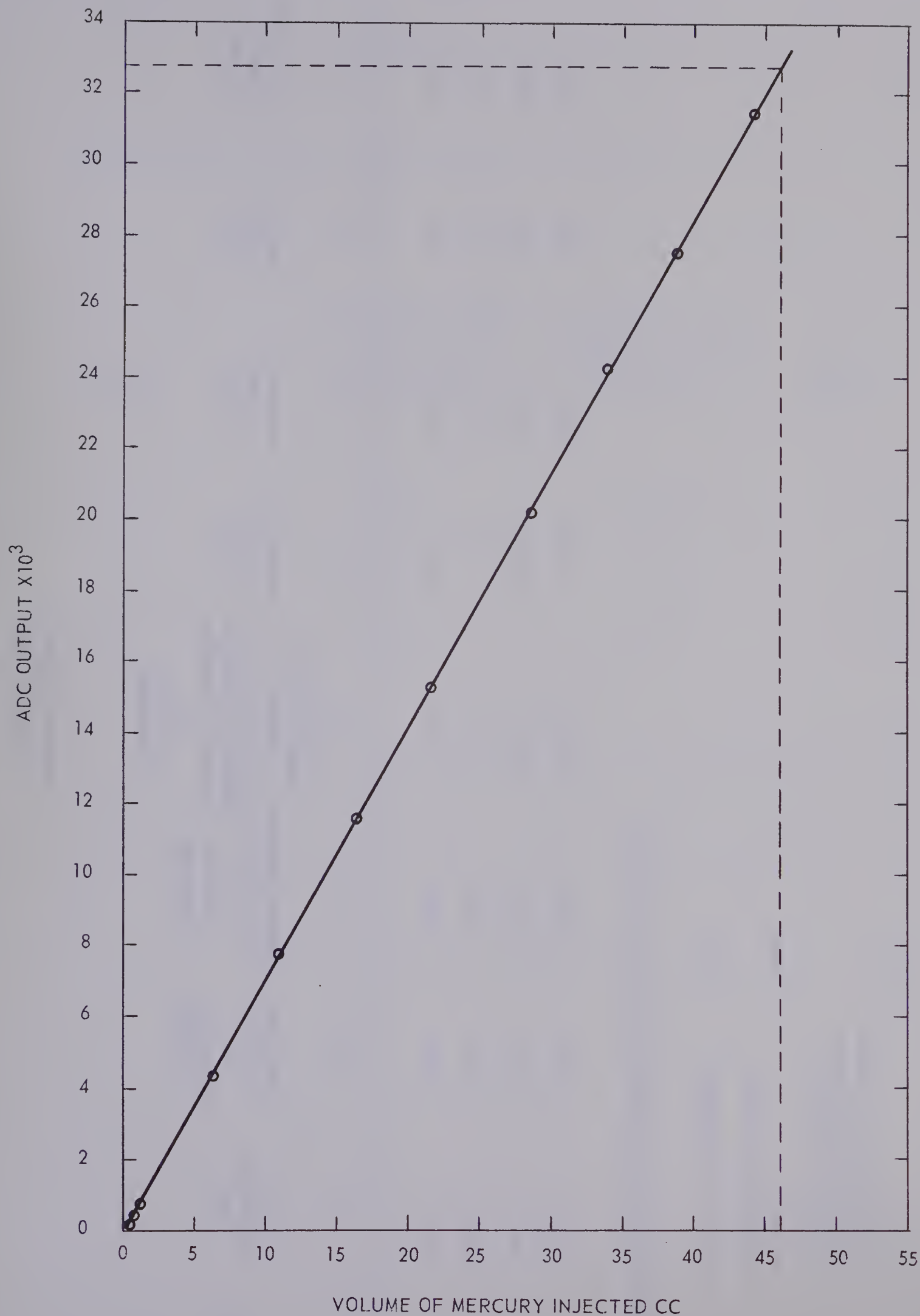


Figure 1X-14

CALIBRATION CURVE FOR LINEAR DISPLACEMENT
TRANSDUCER

Table IX - 12
Summary of Results

Core No.	True Permeability m d	Calculated Permeability m d (from on-line equipment)	Calculated Permeability m d (from manually- operated equipment)	Calculated Permeability m d (from manually-operated equipment corrected for cell expansion and mercury contraction due to pressure)	Percent Error between 1 & 2	Percent Error between 1 & 3	Percent Error between 3 & 4	Percent Error between 1 & 4
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)

6	176.80	150.93	145.77	147.02	- 14.63	- 17.55	- 0.85	- 16.84
7	140.90	130.82	129.44	129.72	- 7.15	- 8.13	- 0.22	- 7.93
8	160.20	174.37	181.39	182.41	+ 8.84	+ 13.22	- 0.56	+ 15.09
9	177.30	170.52	165.22	166.97	- 3.82	- 6.81	- 1.05	- 5.82

Standard Deviation of Permeabilities for Cores 6 Through 9

1. Using On - Line Equipment = 21.70
2. Using Manually - Operated Equipment = 24.60
3. Using Data From Manually - Operated Equipment Corrected for Cell Expansion and Mercury Contraction = 23.75

TABLE IX - 13

Effect of Neglecting Cell Expansion and Mercury Contraction
Due to Pressure on Area Under the $\frac{1}{P^2}$ vs ρ Curves

<u>Core No.</u>	<u>Area Under Curve With Correction Lithology Factor = 0.11328</u>	<u>Area Under Curve Without Correction Lithology Factor = 0.10882</u>	<u>Percent Error</u>
6	0.8740	0.90209	+ 3.21
7	0.8464	0.87916	+ 3.87
8	0.92771	0.96029	+ 3.51
9	1.0436	1.075	+ 3.06

It should be noted that neglection of the effect of mercury contraction and cell expansion due to pressure, causes a maximum and minimum error of + 3.87 and + 3.06 percent in the areas under the $\frac{1}{P^2}$ vs ρ curves for cores 7 and 9 respectively.

EFFECT OF NEGLECTING CELL EXPANSION AND MERCURY
CONTRACTION WITH PRESSURE, ON PERMEABILITY RESULTS

Core No. 7

1. Assuming that the lithology factor remains constant and is equal to F.

(i) Using Corrected Data

$$\begin{aligned} K &= 0.66 \times 0.205 \times F \times 0.8464 \times 10^4 \text{ m d} \\ &= 1145.18 F \text{ m d} \end{aligned}$$

(ii) Using Data Without Correction

$$\begin{aligned} K &= 0.66 \times 0.205 \times F \times 0.87916 \times 10^4 \text{ m d} \\ &= 1189.50 F \text{ m d} \end{aligned}$$

$$\text{Percent Error} = + 3.87$$

2. Assuming that the lithology factor does not remain constant

(iii) Using Correct Lithology factor and corrected data

$$\begin{aligned} K &= 0.66 \times 0.205 \times 0.11328 \times 0.8464 \times 10^4 \text{ m d} \\ &= 129.72 \text{ m d} \end{aligned}$$

(iv) Using incorrect lithology factor and data without correction.

$$\begin{aligned} K &= 0.66 \times 0.205 \times 0.10882 \times 0.87916 \times 10^4 \text{ m d} \\ &= 129.44 \text{ m d} \end{aligned}$$

$$\text{Percent Error} = - 0.22$$

Core No. 9

1. Assuming that the lithology factor remains constant and is equal to F.

(i) Using corrected data

$$\begin{aligned} K &= 0.66 \times 0.214 \times F \times 1.0436 \times 10^4 \text{ m d} \\ &= 1473.98 F \text{ m d} \end{aligned}$$

(ii) Using data without correction

$$\begin{aligned} K &= 0.66 \times 0.214 \times F \times 1.0750 \times 10^4 \text{ m d} \\ &= 1518.33 F \text{ m d} \end{aligned}$$

$$\text{Percent Error} = + 3.06$$

2. Assuming that the lithology factor does not remain constant

(iii) Using correct lithology factor and corrected data

$$\begin{aligned} K &= 0.66 \times 0.214 \times 0.11328 \times 1.0436 \times 10^4 \text{ m d} \\ &= 166.97 \text{ m d} \end{aligned}$$

(iv) Using incorrect lithology factor and data without correction.

$$\begin{aligned} K &= 0.66 \times 0.214 \times 0.10882 \times 1.0750 \times 10^4 \text{ m d} \\ &= 165.22 \text{ m d} \end{aligned}$$

$$\text{Percent Error} = - 1.05$$

APPENDIX X
DISCUSSION OF RESULTS

DISCUSSION OF RESULTS

The calibration curves for the linear displacement and pressure transducers are presented in Appendix IX. These curves were obtained by plotting the ADC (Analog to digital converter) output versus the pressure and cubic centimeters of mercury injected for the pressure and linear displacement transducers respectively.

The pressure transducers were calibrated against the mercury manometer from absolute vacuum to atmospheric pressure and against the pressure gauges from atmospheric pressure to 1500 psig. The linear displacement transducer was calibrated against the scale on the mercury injection pump. The calibration equations for the pressure and linear displacement transducers are presented on pages 28 through 30. While calibrating the pressure transducers the readings were overlapped to check if all the transducers read the same pressure.

Trial runs were made on about six cores to obtain an estimate of the time required to reach equilibrium during each increment of mercury injection. It was observed that at pressures below 50 psia, equilibrium was reached in about one to two minutes, but at higher pressures three to five minutes were required.

It is noticed that a consistent discontinuity exists at atmospheric pressure for data obtained by using manually-operated equipment. This discontinuity could be accounted for by day to day changes in atmospheric pressure, but the size of this discontinuity suggests that besides the day to day changes in atmospheric pressure there might have been significant differences between the barometric atmospheric

pressure and the zero gauge pressure. This could be due to the error in the calibration of the pressure gauges.

This consistent discontinuity does not exist in the data obtained by on-line equipment because the on-line equipment uses absolute pressure transducers which take into account the day to day change in atmospheric pressure and also because the calibration of the transducers smoothens the data.

It should be noticed that in the presentation of the data sometimes six to seven significant figures have been used, but this does not suggest that an accuracy to seven significant figures was obtained. It would be appropriate to say that an accuracy to a maximum of three significant figures was certainly obtained.

Thomeer's²⁵ technique was tried to curve-fit the capillary pressure data obtained in this work, but it was noticed that this technique did not fit the data obtained from the cores used in this work. The data at lower and higher pressures could be fitted with a separate curve by Thomeer's technique but it was not possible to fit one continuous curve through all the datum points.

Alternative to Thomeer's technique it was possible to curve-fit the capillary pressure data by simple least squares method by two different curves at lower and higher pressures respectively. The curve-fits which have been presented in this work were the best fits possible by using the powers of x as basis functions, because it was not possible to use Thomeer's technique.

One possible reason for obtaining two curves to fit this data by Thomeer's technique could be that the cores used possibly have a dual pore size distribution, although the pore geometrical factors and the displacement pressures from this data have the same range as suggested by Thomeer.

Quite some time was devoted to reach some definite conclusion as to why Thomeer's technique did not work. The above mentioned conclusion was the best which could be obtained, although it is something to be looked into in much more detail.

The correction curve for cell expansion and mercury contraction due to pressure is presented in Figure IX-1. This curve was obtained by making a blank run without the core in the cell. The fall in the level of the mercury in the cell with pressure is due to the cell expansion and mercury contraction. The amount of mercury injected into the cell to bring the level of the mercury back to the mark in the upper window of the cell, was noted for every pressure increment. The data so obtained is plotted in Figure IX-1.

When a run is made with the core in the cell it should be noted that the amount of mercury actually entering the core at a certain pressure is not equal to the amount of mercury required to bring the level of the mercury back to the mark in the upper window of the cell. The actual mercury injected is equal to the volume obtained after subtracting from the above volume the amount of mercury contraction and cell expansion at that pressure. This can be read from the plot on Figure IX-1.

Neglecting the effect of mercury contraction and cell expansion can cause an error as large as seven percent in the fraction of pore volume filled with mercury, if the core has a pore volume of approximately 3.5 cubic centimeters.

In calculation of the permeabilities of the cores, the effect of neglecting the cell expansion and mercury contraction would be on the area under the $1/P^2$ vs ρ curve. If the data is corrected for the above effect, it results in a smaller area under the curve. From Table IX-13, it should be noticed that with correction the areas under the curves are from 3.06 to 3.87 percent smaller than without correction.

If we assume that the lithology factor remains constant, then it should be observed from Page 186 that for the maximum case the neglect of the effect of cell expansion and mercury contraction can cause an error as high as 3.87 percent in the permeability. It should be noted, however, that when the effect of pressure on the cell and mercury is accounted for, the lithology factor increases and is not constant, with the result that the percentage error in the permeability caused by neglecting this effect is reduced, as can be seen in Table IX-12 column (7). The maximum error it has caused is -1.05 percent.

From the above facts, it can be concluded that the decision for correcting the data for cell expansion and mercury contraction depends on the purpose for which the data are to be used. In the case of determining permeability, we have observed that it does not make much difference.

If the data are to be used to determine the porosity of the

cores, then for low porosity cores neglect of the above effect would cause an appreciable error in the results, and therefore, it should be accounted for by building-in this correction in the program.

From Table IX-12, it is observed that the permeability results obtained by on-line equipment have the lowest standard deviation and that from the manually-operated equipment without correction for cell expansion and mercury contraction have the highest. The standard deviation is reduced if the cell expansion and mercury contraction due to pressure is accounted for.

The low standard deviation for the permeabilities obtained by the use of the on-line equipment results from the fact that the area under the curve is determined more accurately by the use of numerical integration than by the planimeter. The values of the pressure and volume of mercury injected are also determined more accurately by the use of the on-line equipment because it used calibration curves which smoothen the data and eliminates personnel errors. The use of absolute pressure transducers takes into account the day to day change in atmospheric pressure and eliminates errors like the one caused by switching from the manometer to the pressure gauge. Besides the above advantages of the on-line equipment, the main advantage is the reduction in time for running a core.

It was observed that approximately one hour was required to run one core, and to obtain the permeability with the plots. This time is about one-sixth the time normally required by manually-operated equipment.

This reduction in time will become appreciable when this capillary pressure data are put to more sophisticated problems like (1) determining the surface area of the porous media and (2) determining pore size distribution, etc.

It is the opinion of the author that the use of the on-line equipment is warranted even if the results are comparable to the ones obtained by the use of the manually-operated equipment because of the reduction in time and especially when the IBM 1800 computer exists in the department. The on-line equipment will be especially useful when a large number of cores have to be run.

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